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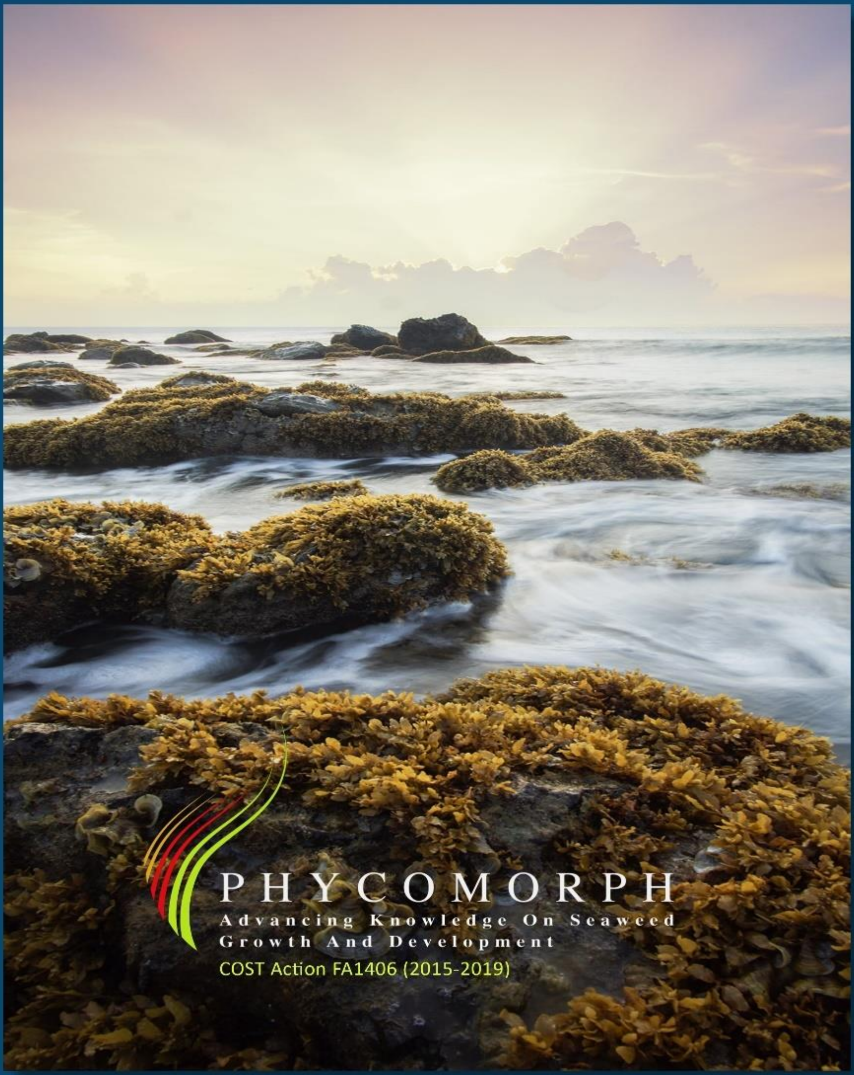
PHYCOMORPH EUROPEAN GUIDELINES FOR A SUSTAINABLE AQUACULTURE OF SEAWEEDS



PHYCOMORPH
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FA1406

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Phycomorph European Guidelines for a Sustainable Aquaculture of Seaweeds

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PREAMBLE

Macroalgae, or seaweeds, are multicellular – usually macroscopic – plant-like organisms that generally live attached to rock or other hard substrata in coastal areas. There are about 10,000 species of algae, of which 6,500 are red algae (also named Rhodophyta), 2,000 are brown algae (Phaeophyceae), and 1 500 are green algae (Chlorophyta and Charophytes). These three groups have very distinct evolutionary histories and display specific ultrastructural and biochemical features (e.g. pigments).

Seaweeds are increasingly employed as feedstock around the world, with an annual production of 30Mt for a ~ €8B value. Seaweeds are thus a promising bioresource for the future and demands for high-value seaweed-derived compounds (cosmetics, food) are on the rise in Europe. However, the production of Europe lags behind that of Asian countries despite its large exclusive economic zone, its high seaweed biodiversity and its international leadership in fundamental research on macroalgae.

Drawing on our long-term experience in plant production and domestication in general, as well as on current knowledge of European and worldwide marine ecology, climate and trade, we explore the reasons for this lag, and offer recommendations for improving seaweed cultivation and harvest.

Based on a detailed analysis of current seaweed aquaculture practices, regulations, health benefits and consumer demands, these guidelines aim to foster sustainability and protection of the marine environment. These guidelines also include expert opinions and assessments from the academic, private and associative sectors, based mainly in Europe, but also on other continents. With this wide scope and using a field-based and scientific approach, we have aimed to produce a robust prospective reference document to support policy-makers and the elaboration of future European regulations.

Dr Bénédicte Charrier, Chair of the COST Action FA1406 "PHYCOMORPH"
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HOW TO USE THESE GUIDELINES

These guidelines are fully in line with the recommendations of the United Nations Policy Brief (Cottier-Cook et al. 2016). This document specifically aims to better understand the current situation in Europe in terms of seaweed cultivation and production, food safety and security, and legislation, with details on the licensing process in the main producing countries. It also identifies the main bottlenecks preventing industrial development.

These guidelines should be considered as scientific advice to help all stakeholders in the sector to understand the different aspects of seaweed aquaculture that need to be taken into account for sustainable development in Europe, and to incite large-scale reflection on this theme among producers, policy makers, national authorities and scientists.

Inter alia, fine details are provided on the legislation and regulations that currently apply to the production and consumption of seaweeds as a food or food supplement. These paragraphs should be taken into account by policy-makers when considering regulations.

The state of play of production levels in the different European countries is provided, highlighting some mismatches between governance, the licensing process and industry. National aquaculture representatives should review these paragraphs.

As Phycomorph is a network of experts mainly specialised in genetics and seaweed life cycles, the scientific focus is on the impact of the cultivation method on the environment: what is grown and how it is grown, highlighting the risk of a loss of local biodiversity. The second priority is food security.

In addition, these guidelines propose details on directions to be followed by research programmes that should be implemented to fill identified gaps in scientific knowledge regarding the domestication, cultivation, production and safe consumption of seaweeds.

All these different recommendations help lift the veil on seaweed aquaculture and identify the ground yet to be covered in order to free up its development to support the related economies while preserving our environment.

Dr Michèle Barbier, Institute for Science & Ethics, France

CONTENTS

GLOSSARY – DEFINITION OF TERMS

Alien: A species, subspecies or lower taxon, introduced outside its natural past or present distribution; includes any part, gametes, seeds, eggs, or propagules of such species that might survive and subsequently reproduce (CBD 2002). synonymous: introduced species, exotic species, or non-native species.

Allele: A variable version of the one gene, which is distinguishable by variations in its nucleotide sequence.

Breeding/inbreeding/outbreeding: While inbreeding indicates crosses between two related individuals of the same population, which are genetically close, outbreeding defines crosses between members from two distant populations (Lynch 1991).

Cultivar: Plants obtained by targeted selection (breeding). Different cultivars can be obtained from the same species.

Domestication: “Domestication is considered a long and complex process during which domesticators select and modify organisms that can thrive in human eco-environments and express traits of interest for human use” (Valero et al., 2017).

DW: Dry weight.

EFSA: European Food Safety Authority.

FW: Fresh weight.

GIS: Geographic Information Service.

IMTA: Integrated Multi-Trophic Aquaculture combines aquaculture of fed organisms (e.g. finfish) with that of extractive organisms consuming dissolved inorganic nutrients or particulate organic matter (seaweeds and invertebrates, respectively), so that the environmental processes at work counterbalance each other (Chopin 2006).

Invasive species: An invasive alien species (IAS) is a species that is established outside of its natural past or present distribution, whose introduction and/or spread threaten biological diversity (CBD 2002).

Kelp: Name given to large brown algae by coastline inhabitants. Still in use.

Life cycle: Duration and steps which an organism goes through, from a single- cell stage, to the next generation. It usually involves an alternation of haploid and diploid generations (haplo-diplobiontic) and sexual reproduction.

Local strains: A cultivated strain or variety whose genetic background is similar to that of the natural population geographically close. The degree of similarity taken into account is directly dependent on the observed genetic diversity of the species in the considered area, compared to distant populations of the same species. It is a relative parameter (“more or less similar”).

MRL: Maximum Residue Limits.

Monoculture: Intensive cultivation of a single species in a given area over a long period (Lemaire & Lemaire, 1975).

Native vs non-native species: While a native species settled in an area, independently from the human activity, a non-native (alien) species is one which has been introduced, deliberately, or not, in the area as a consequence of human activities (Pyšek 1998).

Offshore: The common notion of "offshore" simply refers to "not on land", meaning the cultivation of fish, shellfish or seaweed in cages, long lines or other structures in the sea. In the context of seaweed farming, it is suggested that the term "offshore" be used for large-scale activities in open-sea waters, unlike the farming in coastal waters as practised at present.

Population: A population is a group of individuals belonging to the same species, reproducing mainly between themselves, occupying a common geographical area and playing a particular role in the ecosystem (Odum 1971).

QTL: Quantitative Trait Loci.

Sea vegetable: Marine plant (or piece thereof) used as food.

Seaweed classification: Three broad groups based on pigmentation - brown, red and green - including remarks on different species, with different traits.

Selection programme: A process by which artificial selection for individuals with targeted traits is operated through a succession of crosses between selected genitors.

Strain: This term has no official definition or ranking status in botany but can refer to the offspring from a common ancestor with uniform phenotypes (Usher, 1996). In order to avoid any confusion between the terms “strain” and “lineage” in these guidelines, we make the choice to use “strain” as one isolated individual (e.g single isolated genotype) from either a wild or a cultivated population. “Lineage” will refer to the succession of offsprings from artificial crosses between strains.

Sustainable: To ensure that an activity meets the needs of the present without compromising the ability of future generations to meet their own needs. The concept of sustainable development does imply limits imposed by the present state of technology and social organisation on environmental resources and by the ability of the biosphere to absorb the effects of human activities. However, technology and social organisation can be both managed and improved to make way for a new era of economic growth (Brundtland Report, 1987).

ToI: Trait of interest.

Vegetative reproduction: Asexual reproduction (as e.g. “cloning”) through which a mature organism grows from a fragment of the parental plant or its zoids.

CHAPTER I -

SEAWEED AS AN OPPORTUNITY TO MEET HUMAN NEEDS

Coordination: Rita Araujo (PhD), European Commission, Joint Research Center at ISPRA

Seaweeds are used as raw materials for a variety of applications such as food, health and well-being, agriculture and aquaculture, ecosystem management, and bio-based products. Additionally, they play a key ecological role in coastal ecosystems, with some seaweed communities (e.g. kelp forests) considered as among the most productive habitats on the planet.

Photo credit: Tao Jones from Pixabay

I - ECOLOGICAL IMPORTANCE OF ALGAE IN MARINE ECOSYSTEMS

I.1. Structuring species in coastal food webs and habitats

Seaweeds are essential components of temperate to polar coastal ecosystems, contributing to their production, biodiversity and functioning. Many macroalgae are structuring species in coastal zones, modifying the environment (by changing light, hydrodynamics and sedimentation rates), supporting complex food webs, and providing ecosystem services such as habitats, food, reproductive refugia and shelter to a variety of associated organisms from different trophic levels like apex predators (sea mammals and seabirds), fishes (e.g. atlantic cod, ballan wrasse, goldsinny wrasse, lumpsucker) and invertebrates (gastropods, molluscs, crustaceans and echinoderms) (Reisewitz et al. 2006; Leclerc et al. 2013; Smale et al. 2013; Bertocci et al. 2015), many of which are of economic importance.

Indeed, a parallel can be made between seaweed communities and land forests: *i)* The canopy provides protection from light and some predators; *ii)* Seaweeds physically promote the stabilisation of hydrodynamics and temperature variations; *iii)* The stratification from the canopy to the substratum provides a diversity of micro habitats and ecological niches (seaweeds are then used as substrata for the attachment of individuals and/or eggs); *iv)* Seaweeds serve as food for marine microorganisms, herbivores, grazing land animals (e.g. sheep and cows that go to the shore at low tides) and food supplement for omnivores and carnivores.

I.2. Coastal defence

Given the increasing population densities living in coastal zones, together with rising flood risks due to the combination of sea-level rise, subsidence and climate change inducing-variations in storminess, there is a growing need for cost-effective and sustainable coastal defence, towards which natural ecosystems can make a valuable contribution (Temmerman et al. 2013; Bouma et al. 2014). Nature-based flood defence (also referred to as ecosystem-based flood defence, “Building with Nature”, “Nature-based solutions”) hinges on two important ecosystem services delivered by coastal ecosystems: *i)* attenuation of hydrodynamic energy from waves, and *ii)* reduction of erosion, either directly or indirectly.

All ecosystems that form structures interacting with hydrodynamics will cause wave attenuation. Corals are highly effective in protecting coastlines since the hard substrata and strong shallowing of the water induce significant wave attenuation (Ferrario et al. 2014). As far as vegetation goes, salt marshes and mangroves are typically the most effective in attenuating waves, given their high elevation in the intertidal zone (Bouma et al. 2014; Ysebaert et al. 2011). This results in the vegetation building elevated and erosion-resistant platforms (Bouma 2007; Temmerman et al. 2007), with stiff vegetation being more effective in attenuating waves than flexible ones (Bouma 2005). The lower capacity of flexible blades to attenuate waves may, however, be compensated by their having higher biomass (Bouma 2010). In this way, flexible vegetation such as seagrass may contribute to wave attenuation both directly, by attenuating waves via high biomass, and indirectly, by maintaining an elevated bed-level at tidal flats, so protecting those tidal areas from erosion (Christianen et al. 2013; Ondiviela et al. 2014).

> A study performed in Norway shows that a single kelp individual can support around 40 macro-invertebrate species corresponding to almost 8,000 individuals.

The interaction of macroalgae with waves has been extensively studied, mainly in the context of fundamental ecology (Denny et al. 1985; Gaylord & Denny 1997; Denny & Gaylord 2002; Gaylord et al. 2007), but with much less emphasis on their potential protective role in flood defence (Smale et al.

2013). Based on their physical structure, macroalgae are expected to behave similarly to seagrasses and to contribute to coastal protection by directly attenuating waves, provided that they offer high biomass high up in the water column. In this respect, large fields of aquaculture are promising for coastal defence.

Alternatively, macroalgae may be expected to contribute to coastal protection by protecting tidal flats from erosion if blade density is high and present in the stormy season (see Løvås & Tørum 2001 as an example).

Seaweeds play an important role in:

- Support of complex food webs in coastal systems (habitat, food, reproductive refuge and shelter for many organisms - apex predators, fishes and invertebrates)
- Coastal defence (reduction of hydrodynamic energy from waves & coastal erosion)
- Carbon sequestration (1ha *Ecklonia* sp. *can* reduce 10 tons CO_2 year^{-1})
- Removal of dissolved nutrients (N & P uptake)
- Removal of ions (petrol, dyes).

I.3. Carbon sequestration

Seaweeds are not only responsible for circulating matter but also for sequestering many elements. These organisms support high primary production and biomass in the form of detritus that is exported to other ecosystems, including deep-sea sediments, shallow coastal areas, and intertidal rocky shores (e.g. Duggins et al. 1989; Mork 1996; Krumhansi & Scheibling 2012). Seaweeds are at the base of all biological relationships between organisms and they regulate matter cycles (carbon, nitrogen, phosphorus, silica, etc.). About 80% of the organic carbon produced by seaweeds forms the basis of the entire food web, from direct seaweed consumers (degradation by microorganisms, suspension feeders, detritivores and grazers) to higher trophic consumers (fish, marine mammals and seabirds) (Klinger 2015). Macroalgae also have the potential to play an important role in C-sequestration (Chung et al. 2013), on the one hand since a significant amount of carbon is maintained within algal biomass (Smale et al. 2016). On the other hand, some algae-derived organic matter is exported to other habitats where it may be buried and stored for a considerable amount of time, thereby contributing to natural carbon sequestration (e.g. crude oil/fossil fuel; Hill et al. 2015). Marine algae and plants (e.g. eel grass) have been estimated to be responsible for more than 70% of the world's carbon storage (Chung et al. 2011). One direct effect of this carbon sequestration is that it mitigates ocean acidification (Nellemann et al. 2009). Large-scale seaweed fields planted in the sea can potentially combine the effects of reducing ocean acidification and excess CO_2 in the atmosphere (consequential) while notably increasing biodiversity in otherwise barren areas.

Marine vegetation covers less than 2% of the sea surface
but can sequester up to 70% of the world's CO_2.

In a farm environment, macroalgal growth would contribute to CO_2 sequestration. Coastal seaweed aquaculture combined with the continuous harvest of the algal biomass could locally buffer ocean acidification (Mongin et al. 2016). Chung et al. (2013) estimated that a pilot coastal CO_2-removal belt farm, when populated with the perennial brown alga *Ecklonia* sp., could draw down approximately 10 tons of CO_2 ha^{-1} yr^{-1}. Consequently, the use of CO_2 by seaweeds leads to both biological productivity and photosynthetic carbon storage. This carbon may be trapped in sediment or transported to the deep sea, therefore, resulting in a CO_2 sink. For instance, collecting seaweeds and using them for biofuel production and other industries (fertilisers, food and feed, pharmaceuticals) would contribute to CO_2 mitigation (Duarte et al. 2017). In addition, the replacement of intense CO_2 emission-footprint production systems with seaweed-based systems entailing lower CO_2 emissions have to be taken into account in the Blue Carbon strategy to counter climate change.

II - SEAWEEDS, A RESOURCE FOR MULTIPLE HUMAN NEEDS

Marine bioresources have a high potential as sources of structurally novel and biologically active compounds for a wide range of biotechnological applications in the areas of food production and agriculture, in the development of innovative products for pharmaceutical and nutraceutical applications, for bioremediation technologies and industrial development of new biobased materials, and in the energy sector. The development of marine biotechnologies can, therefore, contribute to addressing global challenges related to food, energy, health, sustainability and resource efficiency, with marine macroalgae being important contributors. Hence, they are currently explored by the industry as new and sustainable sources for a range of different applications.

Seaweeds can be used for human consumption, as bio-fertilisers, for food/feed or bioenergy production, and can provide raw materials for chemicals and pharmaceutical products.

II.1. Human health and wellbeing

II.1.1 PHARMACEUTICALS

Macroalgae are currently being explored as novel and sustainable sources of bioactive compounds for pharmaceutical applications. These organisms produce original secondary metabolites with a variety of biological properties such as cytotoxic antibiotic, anti-viral, anti-inflammatory and anti-parasitic (e.g. Smit 2004; Mayer et al. 2013; Ruan et al. 2018). Many potent antioxidant compounds have already been detected in different macroalgal species, including phlorotannins, carotenoids and sterols, making these marine organisms promising resources of compounds with potential neuroprotective effects, useful in the treatment of neuro-degenerative diseases such as Alzheimer’s and Parkinson’s (Pangestuti & Kim, 2011; Barbosa et al. 2014).

Sulfated polysaccharides from macroalgae have been extensively studied, having demonstrated interesting potential pharmacological uses. They have displayed anti-ulcer effects by preventing adhesion of the infection causing bacteria *Helicobacter pylori* (Besednova et al. 2015). Anti-viral properties have also been attributed to these natural compounds via different action mechanisms such as inhibiting the binding of the virus to the host cells or suppressing DNA replication or protein synthesis (Ahmadi et al. 2015). Anti-cancer or anti-inflammatory and immunomodulatory activities are also being actively explored, but action mechanisms and active-molecule identification warrant further research (Fitton 2015; Deniaud-Bouët 2017).

II.1.2 COSMETICS AND PERSONAL CARE

Different categories of products can be obtained from different seaweed species. As a result, they occupy a variety of niches in the cosmetics sector. Seaweeds are usually used as texturing stabilisers, emulsifiers, bioactive extracts (impacting both cosmetic stability, e.g. shelf life and/or the skin or substratum applied) or colouring agents (Figure 1).

a) Algotherm, a cosmetics company based in France, uses ingredients (extracts, powder) from different macroalgae (e.g. Fucus vesiculosus, Alaria esculenta, Undaria pinnatifida*) for skincare products and beauty treatments.*

*b) Confiança, a soap company from Portugal, produces soaps incorporating algae (*Chondrus crispus *powder).*

Fig. 1. Examples of companies marketing seaweeds in cosmetics.

Macroalgae are a source of vitamins, minerals, polysaccharides, proteins and lipids, which are ingredients of choice in skincare (Pimentel et al. 2018). Also, bioactive secondary metabolites such as terpenoids, polyphenols and halogenated compounds, among others, can be applied for the development of new bioactive extracts. As photosynthetic organisms, seaweeds also produce UV-absorbing compounds such as terpenes and carotenoids, mycosporine-like amino acids (MAAs) and phenolic compounds, which represent useful photo-protective natural ingredients for sunscreen formulation (Guillerme et al. 2017).

Consequently, seaweeds are used in well-being treatments (e.g. in thalassotherapy and algotherapy) which are claimed to have beneficial effects (e.g. beauty and relaxation) and are available in spas and beauty clinics around the world (Mouritsen 2013).

Seaweeds not only contain all essential amino acids and are a rich source of other bioactive molecules with anti-inflammatory effects, but they can also stimulate the uptake of nutrients and bioactives.

II.2. Food

Although seaweeds belong to a diverse group of photosynthetic marine organisms, with a variable chemical composition depending on species, season and habitat, some species offer significant nutritional value and health benefits (reviewed in Holdt & Kraan 2011; Déléris et al. 2016). Most species are characterised by elevated levels of dietary fibres and minerals, and low lipid levels (MacArtain et al. 2007; Dawczynski et al. 2007). The quality of their proteins (Fleurence 2004; Dawczynski et al. 2007; Mæhre et al. 2014) and antioxidant activities, associated with their content of polyphenolic compounds (Wang et al. 2012) and pigments (e.g. fucoxanthin: Fung et al. 2013), make seaweeds an attractive raw material for the provision of bioactive substances with a broad range of applications, especially in human and animal nutrition. In addition to their nutritional benefits, edible seaweed species are used for enhancing the flavours of a variety of products. Many seaweeds along the coast of Europe display these features.

Algal protein content is generally high in red and green algae (10–47% dry weight) and is much greater than that found in high-protein leguminous seeds such as soybean.

II.2.1. HUMAN FOOD

Macroalgae are rich in minerals and essential trace elements, as well as fibres while being low in energy, and, therefore, contribute to a balanced diet. They are generally considered as a viable protein source, with essential amino-acids composition meeting FAO requirements (Bleakley & Hayes 2017).

These organisms are widely used for human consumption, mostly in Asia (China, Japan, Korea) where they have been used as food for many centuries and are increasingly consumed in Europe. More than 70 edible species have been reported in the Chinese diet (Xia & Abbot 1987), but only a selection of these are approved for food in the EU or its Member States. Macroalgae are considered as an important resource from the ocean, with the potential to be exploited as food and developed sustainably (EC 2017). Seaweeds do not compete with food crops for land and freshwater resources.

***Porphyra* sp.[1] and *Palmaria* sp. are top-choice species for seaweed-based protein sourcing due to their high protein content (47% and 30%, respectively).**

While numerous reports exist on the nutritional value of a wide range of seaweed species, few scientific studies have attempted to characterise the sensory profiles of commercially exploited edible species. Some exceptions to this include studies describing the kelp kombu (*Saccharina japonica*) as a rich source of umami flavour, which is directly related to high levels of monosodium glutamate (Ikeda 2002). After harvest, kombu is typically sun-dried and aged for several years to develop its characteristic flavours. Generally, a wide range of molecules including peptides, minerals, low-molecular-weight carbohydrates and volatile compounds contribute to the sensory features of foods (Lindsay 2008). Only a few studies have attempted to correlate sensory profiling of edible seaweeds with their composition in either volatile compounds (López-Pérez et al. 2017; Michel et al. 1997) or free amino-acids (Noda et al. 1981) *(See Chapter VI on Challenges in Food safety).*

Seaweeds are already considered a key element in healthy diets. They are characterised by high contents of fibres, minerals and essential vitamins coupled with low fat and salt content and rich protein fraction.

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[1] Some seaweed previously classified as genus *Porphyra* are now classified genus *Pyropia*

II.2.2. FOOD SUPPLEMENTS AND FUNCTIONAL FOODS

Nutrients, enzymes, metabolites and other compounds from marine bio-resources are also used in nutraceutical applications and the development of functional foods. Seaweeds are a good source of vitamins (A, K, B12), minerals and trace elements that are essential for human nutrition and can contribute to numerous EU-approved nutritional claims (e.g. iodine, magnesium, calcium, iron) relative to bone health, cognitive function, maintenance of normal metabolism, normal growth and muscle function for example. They can also be considered as a potential source for the production of ω-3 and ω-6 polyunsaturated fatty acids (PUFAs) that are essential components of cell membranes (Mišurcová et al. 2011; Pereira et al. 2011). Moreover, they can be used as a source of essential fatty acids including arachidonic acid (ARA) and docosahexaenoic acid (DHA). These lipids are not present in large quantities but at high concentrations of the total lipids/fatty acids.

II.2.3 FOOD-PROCESSING INDUSTRY

Various red and brown seaweed species are used to produce hydrocolloids such as alginates, agar and carrageenans, which are the primary commercial seaweed extracts (Bixler & Porse 2011). Hydrocolloids are polysaccharides, generally of high molecular weight that can be dissolved in water and provide viscosity or gellifying properties. These components are used as a thickening, gelling, emulsifying and stabilising agents and as food additives (E407; Saha & Bhattacharya 2010). The growth of the seaweed hydrocolloid market has slowed in the last decades but continues to rise at a rate of 2-3% per year (Bixler & Porse 2011). The main raw-material providers at the global level are Asian-Pacific countries (Porse & Rudolph 2017). Indonesia is the largest producer of seaweed species supplying agar and carrageenan extracts while China leads the hydrocolloid-processing sector (Porse & Rudolph 2017).

Agar is extracted from red seaweeds that include the European-occurring genera *Gelidium* sp. and *Gracilaria* sp. In the 1980s, Portugal and Spain were among the leading global producers of agar, but they have considerably decreased their production since. European agar production represented 6% of total production in 2015 (Porse & Rudolph 2017). This seaweed extract is used as microbiological and electrophoresis solid media, as a thickener and stabiliser in the food-processing industry, as a dietary product, and as an alternative to animal gelatine (Mesnildrey et al. 2012).

Alginate is extracted from brown seaweeds such as the European-occurring species *Ascophyllum nodosum* and *Laminaria* species. Europe is the world's leading food and pharma-grade alginate producer (Porse & Rudolph 2017). Due to their properties, alginates are used in the food and feed-processing industry and bi-medicine, as stabilisers of colouring agents, and for waterproofing in the textile industry, paper-coating and in wastewater treatment (Lee & Mooney 2012; Mesnildrey et al. 2012; Gao et al. 2017).

Carrageenans are widely used as emulsifier, gelling and stabilisation components in the food-processing, pharmaceutical, cosmetics and nutraceutical industries, and for aquaculture applications (Bixler & Porse 2011; Hurtado et al. 2015). They are extracted from red seaweeds such as the European-occurring species *Chondrus crispus*, *Mastocarpus stellatus* and *Gigartina* species. Currently, these genera account for a minor share of global carrageenan production (Porse & Rudolph 2017).

II.3. Agriculture applications

II.3.1. ANIMAL FEED

Seaweeds can serve as useful alternative feeds for livestock, mostly as sources of valuable nutrients, complex carbohydrates, pigments and polyunsaturated fatty acids. Cereal and plant proteins are frequently used in the manufacture of animal, fish, and human food products but are often lacking in essential amino acids. Macroalgae, however, contain all the essential amino acids and are a rich source of other bioactive products. Several seaweeds investigated so far have shown to contain high protein fractions with potential use in feeds and supplements. However, large knowledge gaps still need to be filled before seaweeds can become a more realistic replacement for today's conventional raw feed materials such as soy products. In Norway, seaweeds have seen a renewed interest as feed ingredients since the 1960s when seaweed meal was produced from kelp.

Seaweeds can be incorporated into the diets of poultry, pigs, cattle, sheep, and rabbits (Makkar et al. 2016). Used a supplement (e.g. at low inclusion rates (< 2% of diet), an inclusion of seaweed meal derived from *Ascophyllum nodosum* (Tasco) in diets can exert a potent prebiotic activity on monogastric and ruminant species (Allen et al. 2001). The potential use of seaweeds to reduce the methane production from cattle has been experimentally demonstrated with *Asparagopsis* sp. (Li et al. 2016) although further work is needed to assess the long-term implications of these findings.

Current *in vitro* studies demonstrate potential benefits in using macroalgal biomass as a sustainable functional feed for beef cattle (Machado et al. 2015). As for poultry, diet supplementation based on fermented seaweed byproducts (*Undaria pinnatifida* and *Hizikia fusiformis*) has been seen to provide the positive effects of growth performance and immune response (Choi et al. 2014). Additionally, the incorporation of red seaweeds into diets has been found to effectively improve chicken health, productivity and egg quality (Kulshreshtha et al. 2014). Similarly, in aquaculture, seaweed diet supplementation has been reported to increase growth rate and provide diverse benefits, namely acting as a prebiotic (Viera et al. 2011; Lozano et al. 2016).

The high protein content of certain macroalgae can also favour their use as feed/supplements for domestic animals, in combination with the multiple nutrients and bioactive compounds described above. Kelps can beneficially supplement diets for dogs and cats by supplying iodine, which is essential for the thyroid gland and immune system (Wolf & Lewter 2017). In summary, the addition of macroalgae as ingredients in superfoods for companion animals offers high-quality vitamins, minerals, cofactors, and enzymes, hence optimising digestive health and boosting the immune system (Dillitzer et al. 2011; Ememe & Ememe 2017).

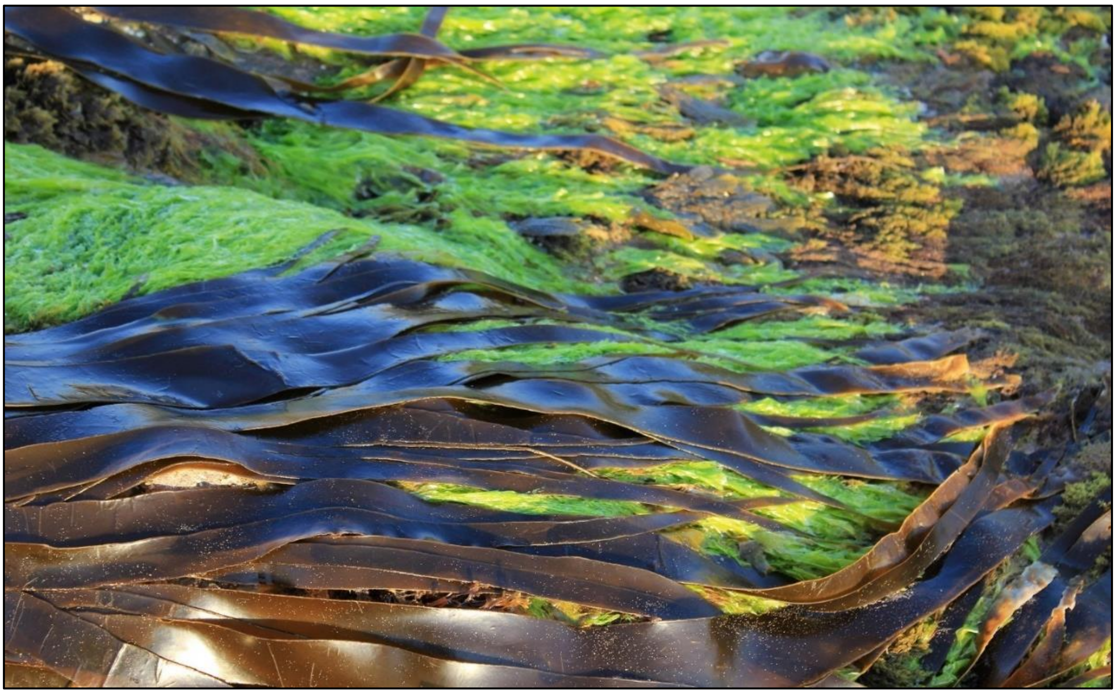

Photo credit: bluebudgie from Pixabay

II.3.2. PLANT GROWTH AND PLANT HEALTH

Seaweeds have been used as fertilisers since the 19th century when harvesters collected them after storm events. Nowadays, seaweed extracts are widely. Nowadays, seaweed extracts are widely used as supplements, biofertilisers and biostimulants for soil and plants in agriculture and horticulture (Wang et al. 2016). Products extracted from seaweeds are claimed to promote higher seed germination as well as to increase yield and resistance against certain diseases and insect pests afflicting many crops (Raghavendra et al. 2007; Selvam et al. 2013; Vijayanand et al. 2014).

II.4. Bioplastics

Bioplastics are an alternative to petroleum-based plastics, offering the possibility of more environmentally-safe and -friendly products. The use of seaweeds to produce bioplastics is a sector in full expansion as the constant need for innovative packaging has led to the development of new materials interacting with the environment and food through the addition of functional ingredients in the packaging structures. Several studies have revealed seaweeds as natural - and edible - producers of activated films with antioxidant (Cian et al. 2014) or anti-bacterial (Siah et al. 2015) properties. Algal polysaccharides such as agar, carrageenan, alginate and also cellulose can be used to produce bioplastic (Ismail et al. 2015; Abdul-Khalil et al. 2017). Besides, poly-β-hydroxybutyrate (PHB), a natural bio-compatible and biodegradable polymer belonging to the polyesters group of bioplastics, has been isolated from different seaweed species (Stabili et al. 2014).

II.5. Biorefineries

An emerging blue bioeconomy provides many possible solutions for relieving current demand on energy, food and chemical resources by the replacement of non-renewable resources such as coal, oil and gas, with resources derived from renewable biomass (Enriquez 1998; De Besi et al. 2015; Loiseau et al. 2016). However, some of these industrial applications are still not economically, energetically or operationally viable, thus requiring optimisation of the value chain. A fundamental unit that stands to foster bio-economic implementations is the development of biorefinery approaches (Lopes 2015). “Biorefinery" is a collective term for the complex system that includes biomass production, transportation, conversion into products as well as their distribution (Santibanez-Aguilar et al. 2015; Martinez-Hernandez 2014). Design of a sustainable macroalgal bio-refinery process capable of generating sustainable food, fuels and chemicals, is largely influenced by local raw-material availability, advances in multiple technologies, and socio-economic conditions (Lopes 2015; Demirbas et al. 2009). The key biorefinery design questions related to the location of systems as well as to the choice of the feedstock and the technologies used to process and convert the latter (Stuart & El-Halwagi 2012; Hennig et al. 2016). Economically efficient, socially and environmentally sustainable conversion of biomass into valuable products is a major contemporary challenge for science, governments and businesses worldwide (Martinez-Hernandez et al. 2014; Karp & Richter 2011; Huisingh et al. 2015). A key challenge is to determine the mix of products and the processes that will maximise the value of the biomass.

Current strategies for food production and renewable-energy generation mainly rely on classic agriculture. However, a key issue for energy production is land availability (Star-coliBRi. European Biorefinery Joint Strategic Research Roadmap for 2020 2011; Henning et al. 2016). An expanding body of evidence has demonstrated that marine macroalgae, when cultivated offshore, can provide a sustainable alternative source of biomass for the sustainable co-production of food, fuel and chemicals (Jiang et al. 2016; Polikovsky et al. 2016; Lehahn et al. 2016; Bikker et al. 2016; Ertem et al. 2016; Nikolaisen et al. 2011; Seghetta et al. 2016; Ruiz et al. 2013). However, to date, macroalgal biomass represents only a tiny percentage of the global biomass supply (~$30 \cdot 10^6$) in comparison to $16 \cdot 10^{11}$ tons of terrestrial biomass (Roesijadi et al. 2010; Pimentel & Pimentel 2008; Pimentel 2012). A recent global assessment showed that in the near future, technologically deployable areas associated with up to

100 m water-installation depth localised 400 km away from the shore, will be able to provide 109 DW tons year^{-1} of cultivated seaweeds, which is equivalent to ~ 18 EJ (Lehahn et al. 2016). It has the potential to displace ~20% of the use of fossil fuels in the transportation sector, or to provide 5–24% of the predicted plant-protein demand in 2054 (Lehahn et al. 2016). Biofuel production from seaweeds is technically possible but promising results from research trials need to be tested at larger scales to assess industrial-scale production potential, equipment life cycle l and the sustainability of the system. The use of seaweeds as feedstock for biofuel production relies on the upscaling of production and optimisation of the biorefinery approach.

A model of the biorefinery was developed for the currently widely cultivated red macroalga *Kappaphycus alvarezii*, which is bio-refined for the co-production of bioethanol, carrageenan, fertiliser and biogas (Ingle et al. 2017). This co-production approach is novel, offering a contrast to the classic processes whereby *K. alvarezii* biomass is used only for carrageenan extraction, after which approximately 60-70% of resultant solid fraction is today considered as waste (Uju et al. 2015). This waste nevertheless contains a high concentration of carbohydrates, which can be hydrolysed into monosaccharides, and then converted into biofuels (Lee et al. 2016; Khambhaty et al. 2012; Hargreaves et al. 2013). Liquid extracted from the raw seaweeds before carrageenan extraction can also be sold as a plant biostimulant (Eswaran et al. 2005).

Multi-extraction of proteins has also been shown recently via enzymatic treatment prior to commercial carrageenan extraction (patent pending). Additional work has demonstrated the co-production of animal feed, chemicals and biofuels from the green macroalga *Ulva lactuca*. Meanwhile, co-production of a mineral-rich liquid extract with cellulose, ulvan, lipid and reducing sugar was recorded for *U. fasciata* (Trivedi et al. 2016). Cascade extraction of salts, pigments and ulvans was shown for *U. ohnoi* (Glasson et al. 2017). Cultivated macroalgae have the advantage of not competing with food crops for land or freshwater resources, thus making them suitable for biofuel production and the replacement of natural gas. Also, seaweed aquaculture can contribute to a sustainable supply of biomass for profitable biofuel production. Moreover, seaweed biogas can potentially deliver beneficial impacts for climate change (i.e. mitigation of global climate change), acidification and terrestrial eutrophication when considering the displacement of coal-based electricity and mineral fertilisers by seaweed biogas and digestate, respectively (Alvarado-Morales et al. 2013).

II.6. Ecosystem management

Seaweeds are capable of photosynthesis and the uptake of dissolved inorganic nutrients and CO_2. Since most of them lack a complex internal transport system, necessary components are usually taken up directly via diffusion in to the frond and stipe. They, therefore, constitute efficient biological agents for dissolved nutrient removal.

The uptake kinetics and saturating storage capacity for dissolved inorganic phosphorus (DIP) and dissolved inorganic nitrogen (DIN) was measured in *Ulva lactuca* over time (Lubsch & Timmermans 2018), displaying the potential use of this species for bioremediation and/or biomass production for food, feed and energy.

Seaweeds have significant bio-accumulation capacities. Acting as a natural cation exchanger, they can remove metal ions from galvanisation or petrochemical wastewaters (Mazur et al. 2016; Cechinel et al. 2016). Likewise, in textile wastewater, macroalgae have successfully demonstrated a capacity to degrade dyes (Holkar et al. 2016). The degradation of dyes by algae can occur through different mechanisms such as consumption, transformation to non-coloured intermediates or adsorption as chromophores on to the algae.

Management of the marine environment requires a holistic approach that recognises its complexity and accommodates its diverse range of uses and users (Turner & Schaafsma 2015). The DPSIR (Drivers-Pressures-State-Impact-Response) or its successor the DPSWR (Drivers-Pressures-State-Welfare-Responses), developed by the European Environmental Agency, are valuable and holistic problem-structuring frameworks, which can be used to assess the causes, consequences, and responses to changes. They have been adopted by the EU Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD) (Elliott et al. 2017). The MSFD and WFD have comparable objectives, but the MSFD focuses on the achievement of Good Environmental Status (GES) in open marine waters whereas the WFD targets good ecological and chemical status in coastal waters (Borja et al. 2010). The two directives, while taking different approaches for the protection of the marine environment (e.g. the scale of assessment), both focus on biological responses, including seaweeds, as quality factors for assessing if GES has been achieved or is maintained (State-Impact). If not, they evaluate the effectiveness of mitigation/restoration measures (Response).

II.6.1 BIOINDICATORS OF WATER DEGRADATION

Seaweeds are sessile, photosynthetic elements at the base of the food web in shallow ecosystems, and as such, are vulnerable and adaptive to local anthropogenic stresses (Hurd et al. 2014). These organisms respond to nutrient and light changes, leading to eutrophication (Cloern 2001; McGlathery et al. 2007) and/or accumulate toxic substances e.g. heavy metals in their cell polysaccharides (Malea & Kevrekidis 2014). Seaweeds have, therefore, been used as quality elements or bioindicators in water-quality monitoring programmes worldwide (EC 2000; EPC 2008). Extensive field and laboratory experimentation has provided mechanistic explanations for their environment interactions. For example, an excess of nutrients in shallow marine ecosystems was shown to shift species composition from late-successional seaweeds to the dominance of opportunistic and often bloom-forming seaweeds (Worm & Lotze 2006) due to rapid growth and/or the colonisation ability of opportunistic species under an increase of nutrient concentration (Viaroli et al. 2008). Seaweed biotic indices represent a recent effort to describe different and complex aspects of communities or other different biological organisational levels by integrating them in a formula producing a single numerical output (Orfanidis et al. 2011). In order to implement the WFD in the Mediterranean Sea, several benthic macrophyte ecological-quality indices are currently suggested for rocky Mediterranean (e.g. Ballesteros et al. 2007; Orfanidis et al. 2011) or Atlantic (e.g. Juanes et al. 2008) coastal waters.

II.6.2. WASTEWATER TREATMENT AND BIOREMEDIATION

Phyco-remediation, also known as industrial ecology, offers many opportunities for macroalgal exploitation still yet to be explored (Olguín 2003). This involves the cultivation of macroalgae for the removal or bio-transformation of CO2, pollutants, and nutrients produced in enormous concentrations (e.g. ammonium) at point sources such as dairies (Wilkie & Mulbry 2002) and piggeries (Kebede-Westhead et al. 2006; Nisiforou 2015).

Seaweeds are able to absorb nutrients (e.g. ammonium and phosphates) and heavy-metal ions (e.g. copper and cadmium) from polluted waters, and therefore they have the potential to be used in tertiary wastewater for water-purification processes eliminating nitrogen, phosphorus and fine particles (Schramm 1991). Pesticides, organic and inorganic toxins and pathogens from surrounding water can also be accumulated in their cells. However, only the opportunistic species from genera such as *Ulva* or *Cladophora* are tolerant to the wide range of salinities and light regimes produced after the dilution of sewage to seawater.

Among the different cultivation systems, Algal Turf Scrubber (ATS) technology - developed and tested both in freshwater and marine ecosystems - depends on highly productive attached and naturally-seeded filamentous algae (Adey et al. 2011). Seaweeds (live or dried) also exhibit the capacity to selectively capture metals and specific cations, with potential use in the remediation or biosorption of polluted effluents (Davis et al. 2003). In addition, a biological charcoal (biochar) obtained from processed seaweeds has displayed interesting properties when applied to agricultural soils by increasing the retention of nutrients and reducing the emission of N_2O. Biochar could, therefore, be applied as a means of promoting soil C-sequestration, thereby also fostering the remediation of degraded and low-fertility soils (Roberts et al. 2015).

Besides their potential for dealing with heavy metals or other industrial wastewater, various seaweeds demonstrate a capacity to remove organic compounds such as chlorinated and aromatic organic compounds. When similar systems are used in acid mine drainage (AMD) effluents, they increase effluent alkalinity and facilitate precipitation of the entrained metals as poorly soluble, but economically-recoverable, oxide and hydroxide salts (Bwapwa et al. 2017). Finally, the so-produced algal biomass can also be fermented to contribute to relatively low-cost biofuel production of ethanol, butanol, or methane.

The biosorption of heavy metals from wastewaters by seaweed is promising. Several studies highlight the capacity of seaweed to reduce the nitrogen and phosphorus content of effluents from sewage treatments.

CHAPTER II

ECONOMIC IMPORTANCE OF SEAWEED

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I - USE OF SEAWEED AS FOOD, A LONG TRADITION

A growing body of archaeological and genetic evidence supports the theory that kelp forests and North Pacific coastal ecosystems may have facilitated the settling of the first human groups in the Americas after the end of the last glacial period (Erlandson et al. 2007; Braje et al. 2017). Extensive and highly productive kelp forests from Japan to Baja California provided a diversity of food upon which early travelers could feed. Remains of nine species of marine algae were recorded on the archaeological site of Monte Verde in southern Chile dating back 14,000 years (Dillehay et al. 2008). The site's inhabitants used seaweed from distant beaches and estuarine environments for food and medicine. These findings support the idea that seaweeds were important to the diet and health of early humans in the Americas. Today, seaweeds are still part of the traditional food of American First Nations and Inuit populations living in the Arctic territories (Wein et al. 1996). They also use seaweed as medicine, tools and materials for handicrafts (Kuhnlein & Turner 1991).

Seaweeds have been used for centuries in Asian cuisine for their nutritional properties and for their unique flavours. In Western countries, macroalgae have not been a significant food source over the past centuries while industrial applications have long been limited to the extraction of phycocolloids (alginate, agar, carrageenan) for the food industry. However, northeast Atlantic countries show historical records of seaweed consumption, with the red alga *Palmaria palmata* being an important source of minerals and vitamins (Hallsson 1961; Mouritsen et al. 2013) in ancient times. The tradition has survived only in Iceland and Ireland where this red seaweed is still consumed, dried as a snack or mixed into salads, bread dough and curds.

II - ECONOMIC IMPORTANCE ON THE GLOBAL LEVEL

The worldwide seaweed industry provides a wide variety of products for direct or indirect human uses, amounting to an estimated total value of US$9 billion per year (Figure 2) (Bixler & Porse 2011; FAO 2015). Growing rapidly, the industry is now active in about 50 countries (FAO 2016). Sea vegetables for human consumption constitute about 83% of total global production (including sea vegetables + food additives i.e. phycocolloids, Craigie 2011), while the remainder is used as fertilisers and animal-feed additives, in medical applications (Zimmermann et al. 2005; Ehrhart et al. 2013) and biotechnological applications (McHugh 2003), and 1.8% goes to unknown usages (Buschmann 2017; FAO 2016).

Worldwide, macroalgal production has increased annually by 6.8% for the last ten years and more than 30 million tons of macroalgae were produced from global capture and aquaculture in 2016 (FAO 2019). In 2016, 97.5% of the total global production of macroalgae came from aquaculture, with Asian countries dominating seaweed-culture production (99.4% by quantity and 99.7% by value, FAO 2019).

In 2016, Korea exported *Pyropia* products worth US$353 million.
The Korean government is encouraging the *Pyropia* export industry
to reach US$1,000 million by 2024.

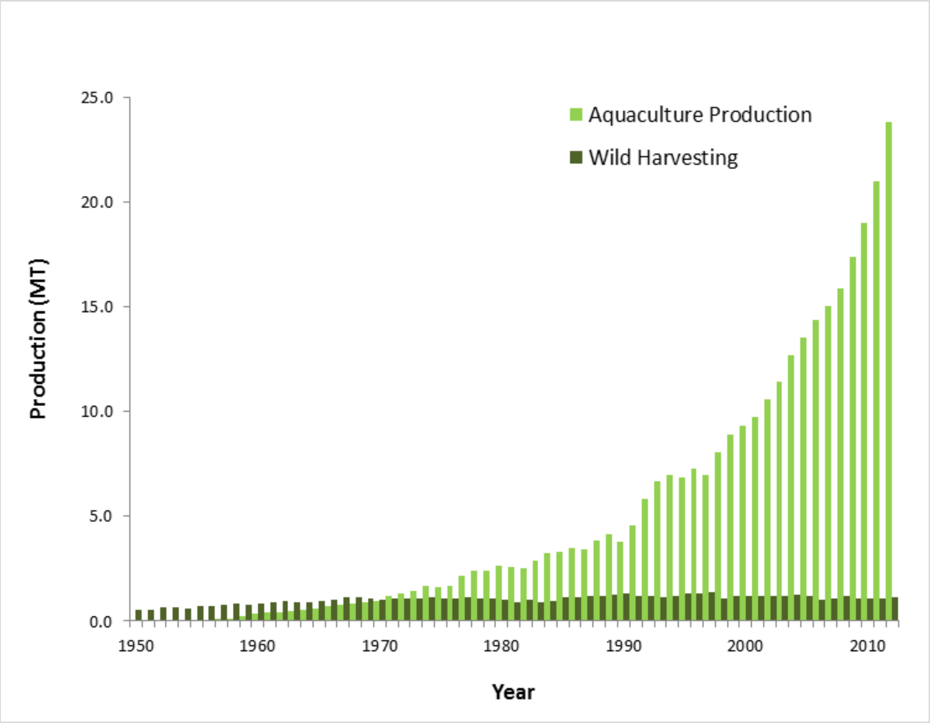


Fig. 2: Global seaweed production: 30 million tons in 2015 for a market of 8.1 billion euros yr^{-1} (Scientific figure courtesy: E. Cottier-Cook, from Cottier-Cook et al. 2016).

Five genera (namely *Saccharina, Undaria, Porphyra, Eucheuma/Kappaphycus* and *Gracilaria*) represented around 98% of the world's cultivated-seaweed production (Suo & Wang 1992; Pereira & Yarish 2008; FAO 2019). *S. japonica* was the most cultivated alga in the world until 2010 when the production of *Eucheuma/Kappaphycus* reached over 10 million tons for a value over €1,079 million (FAO 2019). Red-algal production mainly occurs in Indonesia, the Philippines and Tanzania. *Saccharina* and *Eucheuma/Kappaphycus* are mostly produced as raw materials for the food and food-polymer industries.

Aquaculture of seaweeds is scarce outside Asia (Figure 3), thus triggering a worldwide search for hitherto unexploited natural seaweed resources. In 2016, over 1 million tons of seaweed from the wild were commercially harvested in 29 countries, ranging from cold to tropical coastlines in both hemispheres, with over 32.8% of the biomass harvested in Latin America and almost 26.9% in Europe (FAO 2019). The top producers based on harvesting were Chile and Norway, respectively accounting for 30.2 and 15.5% of the global catches of natural seaweed (Figure 4) (FAO 2019).

Interest in seaweeds, which are predominantly used in the alginate industry, has increased significantly in the past few years amongst European industrial actors in various fields. They are now considered as an important resource with a wide range of applications. Several initiatives and ongoing projects involving both research and commercial actors within the North Atlantic region, are aiming to develop cultivation of seaweeds and biorefinery processes for various applications (Stévant et al. 2017a; Skjermo et al. 2014). A seaweed industry relying on the use of cultivated-seaweed biomass is emerging and expected to grow based on the demand for sustainable protein-rich food and feed sources in developing as well as in developed countries (Skjermo et al. 2014).

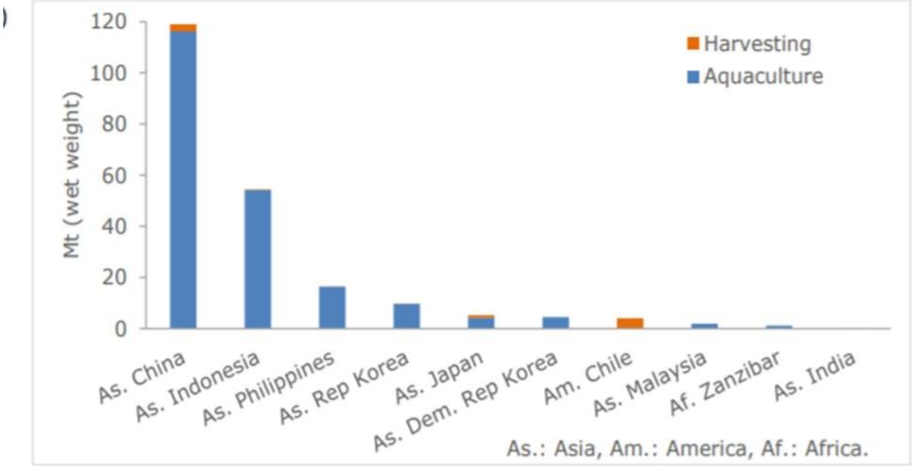
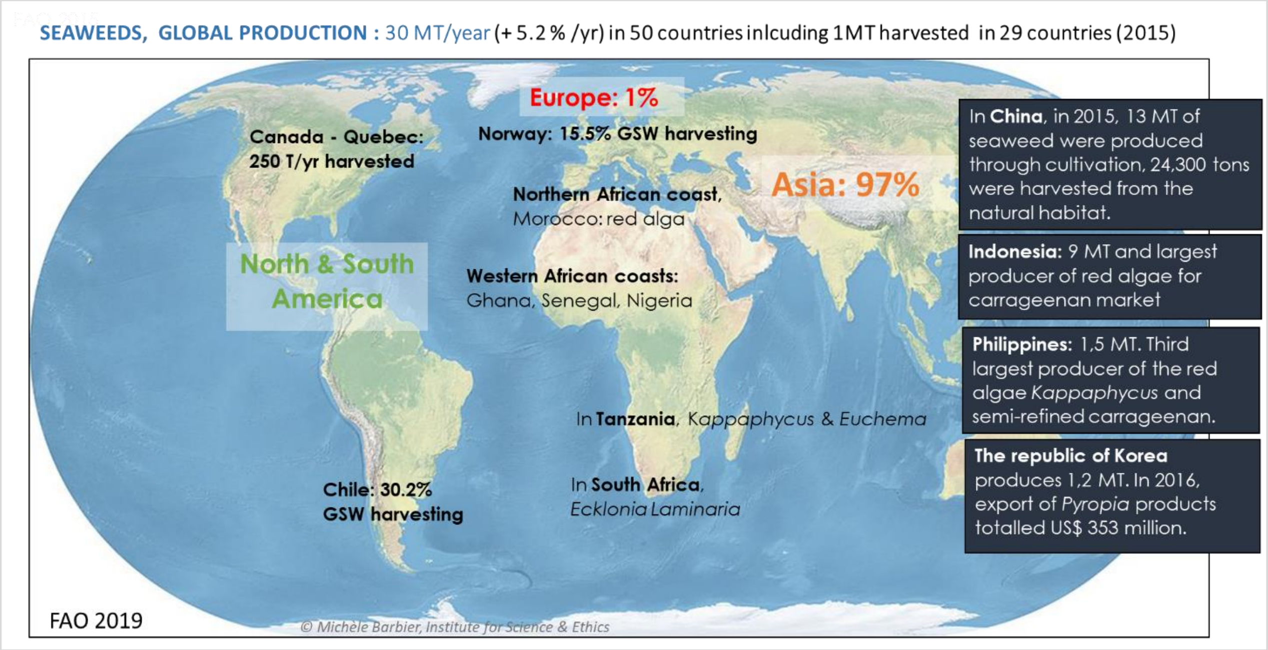


Fig. 3: Total algae production (sum over the period 2006-2015) of the top ten producers at the global level (adapted from Camia et al. 2018).

The production of global products containing ingredients from seaweeds has risen regularly since 2011, with 4% growth reported between 2014 and 2015. Innova Market Insights has reported a 10% increase in launches of global supplements containing seaweed ingredients (2015 vs. 2014) (Selby 2017).


SEAWEEDS, GLOBAL PRODUCTION : 30 MT/year (+ 5.2 % /yr) in 50 countries inlcuding 1MT harvested in 29 countries (2015)

In **China**, in 2015, 13 MT of seaweed were produced through cultivation, 24,300 tons were harvested from the natural habitat.

Indonesia: 9 MT and largest producer of red algae for carrageenan market

Philippines: 1,5 MT. Third largest producer of the red algae *Kappaphycus* and semi-refined carrageenan.

The republic of Korea produces 1,2 MT. In 2016, export of *Pyropia* products totalled US$ 353 million.

Fig. 4: Representation of the world-wide production of seaweeds (© Michèle Barbier, Institute for Science & Ethics).

The health benefits of seaweeds, particularly as ingredients used for innovative flavouring or as a salt substitute, seem to appeal to European consumers. As a result, 37% of seaweed-flavoured food and drink products launched in Europe between 2011-2015 took place in the snack category, according to Mintel's Global New Products Database (2016). Other top categories for new-product development in Europe included sauces and seasonings (12%), bakery products (9%) and soup (8%).

Food and drink products which comprise seaweed ingredients (including kombu, nori/laver and wakame) flavours increased by 147% between 2011-2015 on the European market (Mintel 2016). This growth means Europe is now the second-most innovative region globally when it comes to seaweed-flavoured food and drink introductions. Whilst most seaweed products are launched in the Asia Pacific region, which accounted for 88% of global product launches between 2011 and 2015, Europe released 7% of the total in this period, outpacing both North America and Latin America.

II.1. High- & middle-income countries

II.1.1 CHINA

In 2016, a total of 2,178,000 tons of various seaweeds were produced through cultivation, whilst 24,300 tons were harvested from their natural habitat. Seven seaweed species (i.e. *Saccharina japonica*, *Pyropia haitanensis*, *P. yezoensis*, *Undaria pinnatifida*, *Eucheuma denticulatum*, *Gracilariopsis lemaneiformis*, *Hizikia fusiformis*) are farmed on a large scale from Liaoning Province in the north of China to the sub-tropical Hainan Island in the south of China. All coastal provinces except Guangxi and Hebei, have their independent seaweed farming industries, distributing different species. The entire farming area was estimated at 136,223 hectares. The raft system of cultivation is widespread along various coastlines, on which either brown or red algae are grown, mainly from winter to early spring. Over the years, seaweed has predominantly been used as human food and as raw materials for the phycocolloid industry. The farming industry for seaweeds in China has generated great economic, social and environmental benefits for the society. The scale and area of seaweed cultivation is still steadily increasing there.

II.1.2. THE REPUBLIC OF KOREA

The Republic of Korea is the fourth-largest producer, contributing 1.2 million tons of seaweeds annually (FAO 2017). Among the economically important genera are: *Pyropia*, *Undaria*, *Saccharina*, *Sargassum*, *Ulva*, *Codium* and *Gracilaria* which are used for the food, whereas *Gelidium*, *Pachymeniopsis* and *Ecklonia* spp. which are used as raw materials for the extraction of phycocolloids. Of these genera, *Pyropia* represents 69% of the total value from cultivated seaweeds and, therefore, is the cultivated seaweed with the highest value (MOF 2017, Table 1). The annual production of *Pyropia* increased dramatically since the mid-1990s, and then again since 2000. In 2016, export of *Pyropia* products was valued US$353 million (KCS 2017), and then up to US$500 in 2017, making Korea the top exporter of *Pyropia* in the world. The Korean government announced plans in 2017 to focus on and develop the *Pyropia* industry as a driver for the food industry, encouraging it to reach US$1,000 million by 2024. The *Pyropia* industry in the Republic of Korea is currently worth about US$3,000 million. From its cultivation to processing and export, the production of *Pyropia* is based on traditional methods, and only a small proportion of the process is automatised. However, net profit is high in the *Pyropia* industry, at approximately 32% (compared to net profit of 3-5% in agriculture and 2% in the mobile-phone industry).

Table 1: Production and value of Korean seaweed cultivation in 2016. Data from Ministry of Oceans and Fisheries (2017).

Species	Production (M/T)	Value (US$1,000)
Undaria pinnatifida	496,290 (36.7%)	89,163 (13.8%)
Pyropia spp. / *Porphyra* spp.	409,724 (30.3%)	447,242 (69.0%)
Saccharina japonica	397,852 (29.4%)	70,144 (10.8%)
Sargassum fusiforme	32,762 (2.4%)	22,041 (3.4%)
Ulva spp.	7,158 (0.5%)	6,473 (1.0%)
Codium fragile	4,279 (0.3%)	1,720 (0.3%)
Capsosiphon fulvescens	3,193 (0.2%)	10,757 (1.7%)
Sargassum fulvellum	150 (0.0%)	463 (0.1%)
Gracilaria spp.	24 (0.0%)	18 (0.0%)
Total	1,351,432	648,022

II.1.3 CHILE

Chile is the top producer with 329 707 tons of seaweed biomass harvested in 2016 (FAO 2019). Excavations at Monte Verde (Puerto Montt 42° S) documented the early settlement of America by humans, at least 12,500 years before the present day (Dillehay 1989). From the beginning of this settlement, human populations showed a diversified diet based on both plant collection (including seaweeds) and the hunting of large animals (Dillehay 1989). At present, the macroalgal industry in Chile includes the harvest, collection and cultivation of 15 species. Only two of these are commonly in the human diet: *Durvillaea antarctica* (common name "Cochayuyo") and *Pyropia columbina* (common name "luche"). Both species are harvested from natural populations (Vásquez et al. 2012). Fishermen mainly harvest the Durvillaea fronds, which are dried during summer. The consumption of these dried algae occurs in the following season, when they are rehydrated and incorporated into stews, soups and salads. Also, the stripes of young *Durvillaea* plants are harvested and consumed fresh as a salad item. In this state, the common name of *Durvillaea* is "Ulte". *Pyropia* is consumed in central and southern Chile, and its landing does not exceed 18 dried tons year^{-1}. The production of natural *Pyropia* populations depends heavily on rainy years, showing a high interannual variability. In contrast, *Durvillaea* has shown an increase of landings since the 1990s. *Durvillaea* is exported to Asian countries as an equivalent to widely consumed *S. japonica* (Konbu) for its contribution to dietary iodine levels, especially in human populations far from the coastline. Landings of Cochayuyo exceed 6,000 dry tons year^{-1} (Vásquez 2016).

II.1.4 North America

Traditionally, all macroalgae used for human consumption in North America come from outside sources, placing countries like the United States and Canada among the top importers of macroalgae and macroalgal products in the world (FAO 2017). These data directly contrast with the amount of science that is produced in both countries when it comes to basic research related to macroalgae physiology (NSF 2018). The vast amount of knowledge generated is later used in industrial applications in other countries for strain selection, higher crop yield, by-product productivity and phyto-pathological control.

According to a Vandermeulen report published in 2013 (Department of Fisheries and Oceans Canada), Nova Scotia is home to the largest seaweed-harvesting industry in Canada with 2,000 wet tons *of Chondrus crispus* harvested in 2009, between 20-25,000 wet tons (ft) of *Ascophyllum nodosum* collected in 2010, and 7 – 300 tons (ft) of kelp harvested per year in the natural environment. In Quebec, rockweed represents 90% of the harvest, which does not exceed 200-300 tons per year (all species combined). The harvest currently permitted assigned to companies allow a maximum harvest volume of 700 tons per year. In Canada, aquaculture is only performed for sugar kelp (*S. latissima*) and represents 5-6 tons (ft) per year, mainly in three cultivation sites. In Canada, irish moss (*Chondrus crispus*) is the only species cultivated in land-based outdoor tanks. However, the informations on the volumes producted by the company Acadian Seaplants Ltd in Nova Scotia are confidential. Regarding at-sea cultivation, commercial aquaculture is only performed for sweet kelp (*S. latissima*) and winged kelp (*A. esculent*a). The biomass produced in Bay of Fundy, Nova-Scotia is not known, but the production in Québec represents 5-6 tons (ft) per year, mainly in three cultivation sites located in the northern part of gulf of St Lawrence, i.e. in Paspébiac bay and in Cascapedia Bay, along the Gaspé Peninsula, and in the Bay of Sept-Îles, on the north coast of Québec (Tamigneaux and Berger, 2018; Tamigneaux and Johnson, 2016).

Sugar kelp (*S. latissima*) and winged kelp (*Alaria esculenta*) have been the main exploited and cultivated species in the United States since the 1960s. With little governmental incentive or general-public interest in the cultivation of macroalgae, the industry remains incipient and unable to meet the exponential national demands for macroalgae and macroalgal by-products (Kraemer et al. 2014; Kim et al. 2017). Other less successful attempts at cultivation were made using *Pyropia yezoensis* (*Porphyra*) in 1994 in the State of Maine (Chopin et al. 1999). Later, in 2014, a *Pyropia* seedstock production manual was developed to stimulate and guide local aquaculture farmers in order to cultivate the species in the state (Redmond et al. 2014, but, to date, there are no commercial *Pyropia* farms in the U.S.).

In 2017, the U.S. Department of Energy announced US$22 million in funding through the Advanced Research Projects Agency-Energy (ARPA-E) for 18 innovative projects as part of the Macroalgae Research Inspiring Novel Energy Resources (MARINER) programme. MARINER projects will be responsible for developing tools required to enable the United States to become a leading producer of seaweeds, helping to improve U.S. energy security and economic competitiveness (DOE 2017). The list of species includes *Saccharina* in the Northeast and *Sargassum* spp. in the Gulf of Mexico and Caribbean. To be successful, this enterprise will need to be supported by an entirely new set of cultivation techniques, strains and cultivation-farm locations. Local communities and known aquaculture leaders in the industry will be invited to come aboard and share the socioeconomic advantages that come with a strong macroalgal industry, thus breaking the local dogma that macroalgae is not an option for open-water cultivation (Kim et al. 2017). However, the MARINER projects are currently restricted to offshore waters due to at least 120 US Federal laws that can affect macroalgal-aquaculture adoption, either directly (50 laws) or indirectly (70 laws). Restrictions also apply to several states with the potential to become industry hubs, through 1,200 state statutes that regulate aquaculture in their near-shore waters (Getchis et al. 2008). One of the first aims of MARINER should be to create protocols to be presented to elected officials, in order to promote changes to these laws in the near future, thus allowing further exploration of the United States shoreline for algaculture.

II.2. Low-income countries

The production of seaweeds has increased significantly across Southeast Asia over the last four decades as a result of increased access to coastal areas. However, the sustainability of this industry is challenged by climate change, disease outbreaks, market instability and competition from other growing sectors in the region (Hurtado et al. 2014). Red algae are the primary raw materials for carrageenan, for which global demand has increased since the late 1960s and surpassed the availability from harvested wild stocks (Valderrama et al. 2015). This led to the discovery of carrageenan-rich *Eucheuma spp.* in the Philippines, and as a consequence, its cultivation increased rapidly due to low labour costs and led to the exponential growth of carrageenan supplied by Asia (Valderrama et al. 2015). The predominant market for carrageenan raw materials is currently dominated by the demand for processed dairy products (e.g. frozen desserts and ice cream), followed by that for pharmaceutical products - both of which are continuing to grow (Hurtado et al. 2015; Mulyati & Geldermann 2017). Following the establishment of red-algae cultivation in the Philippines, the industry spread across Indonesia, where *Kappaphycus alvarezii* and *Eucheuma* spp*.* were introduced. These species have now been introduced across selected parts of Asia and Africa, where large volumes are produced (Valderrama et al. 2015).

II.2.1 SOUTH ASIA

2.1.1. INDONESIA

Indonesia is now the largest producer of red algae globally, having recently over-taken the Philippines. This is the result of increased utilisation of the extensive coastline due to both government support for the growth of this sector, and increased shelter from extreme climatic events such as typhoons compared with the Philippines (Hayashi et al.2010; Hurtado et al. 2014).

2.1.2 PHILIPPINES

The geographic location of the Philippines, east of the Pacific Ocean and west of the western Philippine Sea, fosters an abundance of diversified seaweeds. However, only a few seaweeds are cultivated commercially in the country, i.e. *Caulerpa lentillifera*, *Gracilaria firma* and *G. heteroclada* in brackish-water ponds while *E. denticulatum*, *K. alvarezii* and *K. striatum* are cultivated in marine waters. *Eucheuma* sp. and *Kappaphycus* spp. comprise almost 95% of the country's total production and are hence considered to have been the flagships of the seaweed industry since the early 1970s to the present.

The commercial farming of *Kappaphycus* was introduced to the Philippines in the early 1970s (Doty 1973; Parker 1984; Doty & Alvarez 1978). As a major source of livelihood, it has brought tremendous economic benefits to more than 200,000 coastal families (Valderrama et al. 2013; Hurtado 2013), and today, has been introduced to more than 30 countries world-wide (Ask et al. 2003; Hurtado et al. 2016). The Philippines is currently the third-largest producer of *Kappaphycus* and semi-refined carrageenan following Indonesia since 2007 and China since 2004 (Neish & Suryanarayan 2017).

Despite a number of seaweed-farming success stories in the Philippines, there is a need to diversify seaweeds and seaweed products in order to ultimately increase revenues along the whole value-chain. The Philippines currently focuses most of its efforts on a single-stream process, which is the production of semi-refined and refined carrageenan, mainly for food ingredients (Neish & Suryanarayan 2017), with the exception of newly-launched *Kappaphycus*-based personal-care products (July 2017) (Morada personal communication). Such changes are required to enable the country to cope with the increasingly varied demands of the global market. Despite the fact that the Philippines initiated the cultivation of red algae and was a major player in the successful introduction of *Kappaphycus* to many other countries, further increases in production have been limited by climate instability and disease outbreaks (Cottier-Cook et al. 2016).

Further growth in the production of red algae in the Philippines has been limited by climate instability and disease outbreaks.

II. 2.2 AFRICA

In Africa, the seaweed industry is limited to a few countries. It is particularly well established in the United Republic of Tanzania and South Africa.

2.2.1 UNITED REPUBLIC OF TANZANIA

Tanzania is a significant exporter of red algae. *Eucheuma* exports started in the early 1940s using wild-stock harvesting and evolved in the early 1980s to seaweed farming (Sen 1991). Tanzanian production, predominantly from Zanzibar, is dominated by *Kappaphycus* and *Eucheuma* (FAO 2014). The industry is an important source of employment in coastal communities. In particular, women in coastal communities have been financially enabled by income from cultivated seaweed (Msuya 2006). In 2005, the Tanzanian government adopted a Seaweed Development Strategic Plan (SDSP) which called for the expansion of *K. alvarezii* due to its higher farm gate price (Msuya et al. 2007). Following the SDSP, production volumes of cultivated seaweeds increased, but more recently the industry suffered a series of disease outbreaks which caused the collapse of cultivation in certain areas and contributed to the volatility of farm gate prices for farmers.

2.2.2 SOUTH AFRICA

Seaweed aquaculture has developed significantly over the last few decades, particularly in combination with abalone aquaculture. The most produced genus are *Ulva* species., with production reaching more than 2,000 tons in fresh biomass (Amosu et al. 2013; FAO 2019). The wild-seaweed harvesting of kelp *(e.g. Ecklonia*), however, remains the principle source of macroalgal production in South Africa. Mozambique, Namibia, and Madagascar have also developed their production capacity of seaweeds (FAO 2012).

2.2.3 NORTH AFRICAN COAST

Morocco has an established seaweed industry based on the harvesting of wild *Gelidium* species on its Atlantic coasts. This industry expanded in the early 1990s, particularly based on this red algae, extraction of agar and its export (McHugh 2002). However, access to the wild resource is now regulated. For other countries from North Africa, no major seaweed industries have developed yet. Tunisia has shown an increasing interest in developing this sector, strengthened by the results of research mostly on *Gracilaria* cultivation (Ajjabi et al. 2018) and the biotechnological potential of seaweeds.

2.2.4 West African coast

In Ghana, seaweed farming is being developed through the SeaBioGh project (2015-2020), in partnership with the Danish Government. The project aims to make seaweed farming a new business for coastal communities to ensure a reliable source of income for local livelihood (Addico & deGraft-Johnson 2015). In Senegal, harvesting activities have also been reported (Amosu et al. 2013; McHugh 2002). Initial studies were also conducted in Kenya (Yarish & Wamakoya 1990) and Nigeria (Oluwatobi et al. 2017) to develop this sector. Whilst, in general, the seaweed industry is still under development on the African continent, coastal countries are currently committing to boost it in order to embrace Blue Growth strategies.

II.3. Relevance for the United Nations Sustainable Development Goals

II.3.1. Vision for a sustainable future

Seaweed aquaculture already provides income to millions of families in rural coastal communities in areas where few opportunities exist, and it has enabled women to become economically active. The future of this industry is endangered by out-breaks of seaweed diseases and pests, the introduction of non-indigenous pests and pathogens due to movements of seaweeds between regions and continents, and unsustainable farming practices and climate change.

Safeguarding the sustainable development of the global seaweed aquaculture industry can contribute to several of the UN Sustainable Development Goals (SDGs). These goals include: no poverty, zero hunger, gender equality, decent work and economic growth, industry, innovation and infrastructure, responsible consumption and production, climate action and life below water.

A recent United Nations University Policy Brief (Cottier-Cook et al. 2016) specifically highlighted eight recommendations for how to develop this industry sustainably and identified the key ecological and socio-economic challenges preventing the sustainable economic growth of this industry. From these, a four-year multi-national project – GlobalSeaweed STAR - was launched in 2017. The project endeavours to work with developing countries to build capacity and to ensure legislation and farm practices are improved to help countries fulfil the UN SDGs previously described.

II.3.2. Management of exploitation practices to ensure the sustainability of exploited resources

The seaweed industry is the fastest-growing of all aquaculture sectors globally, with an annual growth rate of 10% and a turnover value of US$4.8 billion (FAO data on aquaculture in brief 2017). The rapid expansion in this industry can result in unforeseen ecological and societal consequences and management of resources must ensure that their sustainable use is taken very seriously to avoid disease outbreaks, introduction of non-indigenous pests and pathogens, reduction in the genetic diversity of native seaweed stocks, changes in farm-management practices (intensification of culture, illegal use of algicides/pesticides), consequences for the wider marine environment (algicide and pesticide use, introduction of invasive species, alteration of ecosystem structure and function, overexploitation of wild stocks), catastrophic socio-economic impacts on the communities reliant on seaweed production (Cottier-Cook et al. 2016). This management of “risk” and “sustainability” should be based on scientifically proven evidence, be acknowledged as an essential component for establishing a balance between economic growth and ocean health and be incentivised by policy makers. The below management recommendations (Table 2) are based on the initial thirteen recommendations reported in the United Nations Policy Brief (Cottier-Cook et al. 2016) highlighted by the peer-reviewed paper from Rebours (2014).

Table 2: Main recommendations for sustainable aquaculture development, UNU Policy Brief.

Cottier-Cook et al., 2016

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

The FAO and some countries have also edited additional recommendations for management services, such as:

i) The Farming of Seaweeds (IOC 2012) in the western Indian Ocean, clearly presents the methods and techniques for farming *Spinosum* and *Cottonii* seaweeds. The booklet also described the range of difficulties and challenges that are likely to arise, thus enabling stakeholders (including farmers, private-sector investors, governments, donors and NGOs) to benefit from experience and achieve a "win-win" situation. Through understanding and shared experience, it becomes feasible to develop, in partnership with coastal communities, an industry worth millions of dollars.

ii) A Guide to the Seaweed Industry (FAO 2003), which is designed to help those asked to make decisions concerning the seaweed industry when they have little background knowledge. Such decisions may be about the regulation of various sectors of the industry, assistance to support its technological development or financial investment. The targeted group of decision-makers may have roles in bodies such as government agencies, development banks, national and international aid and development organisations, NGOs and financial institutions.

iii) Korea: Seaweed aquaculture: Cultivation technologies, challenges and its ecosystem services (Kim et al. 2017). This review addresses challenges to overcome in terms of science and social acceptability (e.g. development of strains with thermo-tolerance, disease resistance, fast growth, high concentration of desired molecules, reduction of fouling organisms, development of more robust and cost-efficient farm systems that can withstand storm events in offshore environments). The paper also summarises the ecosystem service roles of various seaweeds grown in aquaculture and their economic values.

II.4. International and regional conventions for biodiversity

The rapid expansion of the global seaweed industry over the last four decades preceded the establishment of appropriate biosecurity and legislative structures required to manage the industry sustainably in a manner consistent with other aquaculture sectors.

The European, Canadian, and Latin American seaweed industries rely on the sustainable harvesting of natural resources. As several countries wish to increase their activity, harvesting must be managed according to integrated and participatory governance regimes in order to ensure production with a long-term perspective. Development of regulations and directives enabling the sustainable exploitation of natural resources must, therefore, be brought onto the national and international political agenda in order to provide and ensure environmental, social, and economic values in appropriate coastal areas around the world. In Europe, Portugal requires an appraisal of seaweed-management plans while Norway and Canada have already developed and implemented coastal-management plans including well-established and sustainable exploitation of their natural seaweed resources. Meanwhile, in Latin America, different scenarios of seaweed exploitation can be observed, but each country is in need of long-term and ecosystem-based management plans to ensure that exploitation is sustainable (Rebours et al. 2014). These plans are required particularly in Peru and Brazil, while Chile has succeeded in establishing a sustainable seaweed-harvesting plan for most of their economically important seaweeds. Furthermore, in both Europe and Latin America, seaweed aquaculture is at its infancy and development will have to overcome numerous challenges at different levels (i.e. technology, biology, policy). There is, therefore, an urgent need for regulations and establishment of “best practices” for seaweed harvesting, management, and cultivation. Trained human resources will also be required to provide information and education to the communities involved, so as to turn sustainable seaweed utilisation into a profitable business and provide better income opportunities to coastal communities.

In developing countries, lack of regulation has already resulted in the unchecked spread of pests and diseases and non-native species in seaweed farms and their surrounding environments in Asia, Africa and Latin America. The lack of biosecurity measures and global legislation governing the cultivation of seaweeds and their movement between regions and continents, have been identified as one of the main challenges to tackle to safeguard a sustainable seaweed industry (Cottier-Cook et al. 2016).

Seaweeds, being neither plants nor animals, currently falls between the terrestrial and aquatic remits of agencies normally responsible for national biosecurity, although recently the International Plant Protection Convention (FAO/IPPC) produced recommendations for the inclusion of "aquatic plants" in phytosanitary measures (FAO 2017). However, the current situation regarding the protection of genetic resources and the regulation of food safety of cultivated seaweeds is unclear in the Nagoya Protocol (for access and use of genetic resources) as well as the Cartagena Protocol on Biosafety, both of which are governed by the Convention on Biological Diversity (CBD). Fortunately, lessons can be learned from past situations where strict biosecurity measures have been introduced to protect farmed stock and wildlife, at the farm, zone, national, regional and global levels in terrestrial and aquatic animal systems following major disease and pest outbreaks (Cottier-Cook 2016).

Both the social and environmental impacts of the cultivation of seaweeds are poorly regulated in most of the countries involved in this industry. The legislation covering seaweed aquaculture is highly country-dependent and poorly coordinated, bringing direct consequences on cultivation practices, access to coastal resources, and the resilience of seaweed farmers to deal with disease outbreaks or natural disasters. The current weak participation of certain developing countries in the seaweed market could therefore be reversed by strengthening cooperation with countries active in seaweed management and aquaculture.

The seaweed aquaculture industry is the fastest-growing of all aquaculture sectors globally, with an annual growth rate of 10% and a value in excess of US$ 4.8 billion.

III - SEAWEED PRODUCTION IN EUROPE

III.1. Harvesting and cultivation

Consistent data about seaweed production is difficult to find and is also subject to caution as it is rarely made clear whether the data refers to raw or dried material. The total volume is today still uncertain as in some cases, reporting processes on the production of seaweed biomass is not yet in place in some countries where activity is underway. The FAO global-production statistics database provides the most comprehensive data on seaweed-production volume but is likely to be inaccurate in some cases (for instance, the red-seaweed production volume is believed to be over-estimated). FAO statistics are nevertheless the only source of data covering all countries in the world. According to this database, 1,091,266 tons were harvested and nearly 30 million tons of macroalgae (brown, red and green seaweed) were produced from aquaculture in 2016, with production increasing by 6.8% in the world.

Initial results reported by Camia et al. (2018) assessed EU biomass production, uses, flows and related environmental impacts for the sectors of agriculture, forestry, fishing and aquaculture, and algae, provide quantitative estimates and highlight uncertainties and remaining gaps. The report was framed within the Joint Research Center (JRC) biomass study and is meant to support the EU bioeconomy and related policies. For centuries, European coastal populations have harvested seaweed for domestic purposes and later for industrial uses. The European seaweed industry is mainly based on the harvesting of natural resources of macroalgae. However, the increased demand for seaweed biomass by the industrial, processing industry has pushed harvesters to search for more effective, sustainable harvesting techniques and to establish rules for managing the activity. The mechanization of harvesting began at the start of the 1970s, and seaweed activity coincided with a high demand for raw materials by the processing industry. Some species are still harvested manually. Harvesting and the management of seaweed resources is often under the responsibility of the processing industry or of fishers' organisations.

European production had remained stable at above 350,000 tons until 2000 and since decreased to 294,774 t in 2016 (Figures 5 and 6). There is substantial harvesting of *Laminaria* spp. and *Ascophyllum nodosum*, which are mainly used as raw materials for the production of alginates, animal feeds and supplements and plant biostimulants. The reversal of this descending trend in seaweed production in Europe will depend on stable, sustainable access to raw materials, the development of added-value products and the transfer of expertise about aquaculture between the developed and less-developed regions.

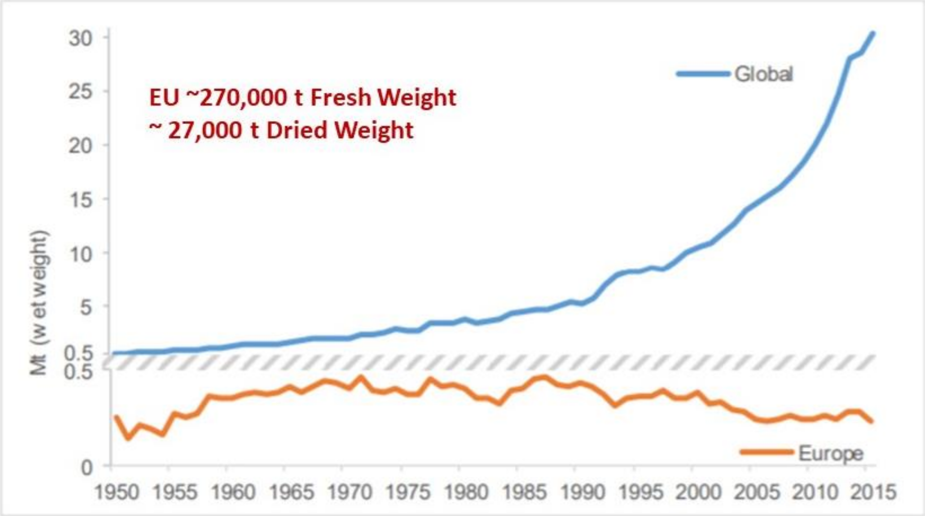


Fig. 5: The EU (incl. Norway) represents less than 1% of the world-wide production of various seaweeds (adapted from Camia et al. 2018).

European aquaculture of seaweeds started in 1985 and today attains 1,450 t with a value of €237,041 (FAO 2019). The main species farmed and already sold on the European market are *Saccharina latissima*, *Alaria esculenta* and *Ulva* sp*.* On a smaller scale and for niche markets, there are also: *Porphyra* spp., *Palmaria palmata*, *Codium tomentosum*, *Gracilaria gracilis* and *Laminaria digitata*. There are only poor data available on the European production of seaweed from aquaculture. *S. latissima* and *A. esculenta* are the main species, produced commercially from aquaculture in France, Norway, Faroe Islands, Ireland, Spain and possibly a few other countries. In Spain, the official statistics for seaweed production are often incomplete, but according to information provided by the regional government of Galicia, the maximum production achieved for *Saccharina latissima* was 11 tons (wet weight), for *Undaria pinnatifida* 5 tons, and for green and red algae less than 1 ton combined. In Portugal, seaweed aquaculture is a reality since 2014 but information has not been made public because there are less than 3 companies operating (data protection issues); this rule is changing from 2018 (Helena Abreu, ALGAplus, personal communication).

The European seaweed industry is dominated by Norwegian, French and Irish production. Iceland, the Russian Federation, Spain, Portugal, Italy, Estonia and Denmark are small suppliers but under development. The presence of a processing industry is a major component for the existence of seaweed production. Processing facilities are always located close to production areas. Although the uses of various seaweeds have changed over time and the species differ between countries, the introduction production of alginates is still the main activity. Despite strong development of mechanized harvesting boats, there is still a significant amount of activity conducted by on-foot gatherers. Their status is not fully recognized in all European countries, leaving room for further legislative debates. The management of seaweed harvesting and collecting has been inherited from the various traditions which have regulated access to the foreshore and marine resources. However, in most cases, public authorities, local or national, fisher organizations (where they exist), and the processing industry are jointly involved in producing harvesting or marketing-related rules. Due to the low competitiveness against production within southern countries and despite rising world demand, the production of seaweeds in Europe has decreased in the past decade. The processing industry is also unsure about its willingness to continue working in Europe which partly compensates for the lack of products by external supply. Production of selected, edible seaweeds for salads and ingredients is growing, but still a marginal activity. There is also a growing demand for a large variety of macroalgal species by biotech SMEs. Seaweeds also represent an opportunity to be exploited as part of the planned development of feedstocks for biofuel production. There are prospects raised by the processing industry that might completely restructure the whole seaweed industry in the near future, both in terms of wild-stock exploitation and development of aquaculture. The rise of conservation claims has also modified the way harvesting and processing are performed as the wild resource must be sustainably exploited in balance with the restructuring and management of wild stocks.

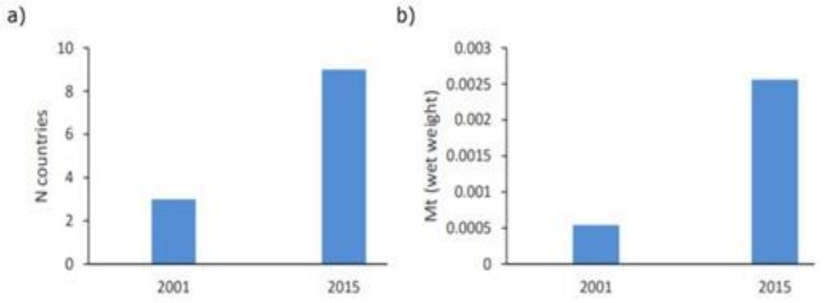


Fig. 6: Temporal evolution of macroalgal aquaculture production in Europe. Columns on the left show the number of countries with algal aquaculture facilities and on the right is depicted the total amount of biomass supplied by these production methods (Camia et al. 2018).

Questions related to seaweed exploitation in Europe:

Is the available, sustainable biomass of various seaweeds being under-valued in Europe?

If one considers raw-material costs vs the profit margins which can be made with higher-value food and biologically active extracts, then the producers of the raw materials (seaweed farmers) are NOT getting fair value for their efforts! This situation needs to change and there should be a more fair distribution of the value-chain?

Would a more equitable valuation of the raw material be attractive for investment and innovation?

TO ANSWER THESE QUESTIONS, A GLOBAL MARKET ANALYSIS IS REQUIRED

III.2. Agenda for the European bioeconomy

The bioeconomy includes several sectors that produce, process and re-use sustainably renewable, biological resources. The main objective of the European Bioeconomy Strategy (Figure 7, with the Action Plan revised in 2018) is to promote the development of an innovative, resource-efficient and competitive economy, combining the sustainable use of renewable biological resources. The aim is to provide food and services to a growing population, with the optimisation of the value-chain towards waste reduction and nutrition security, under the current scenario of environmental pressures. The Strategy is focused on providing support to five societal challenges.

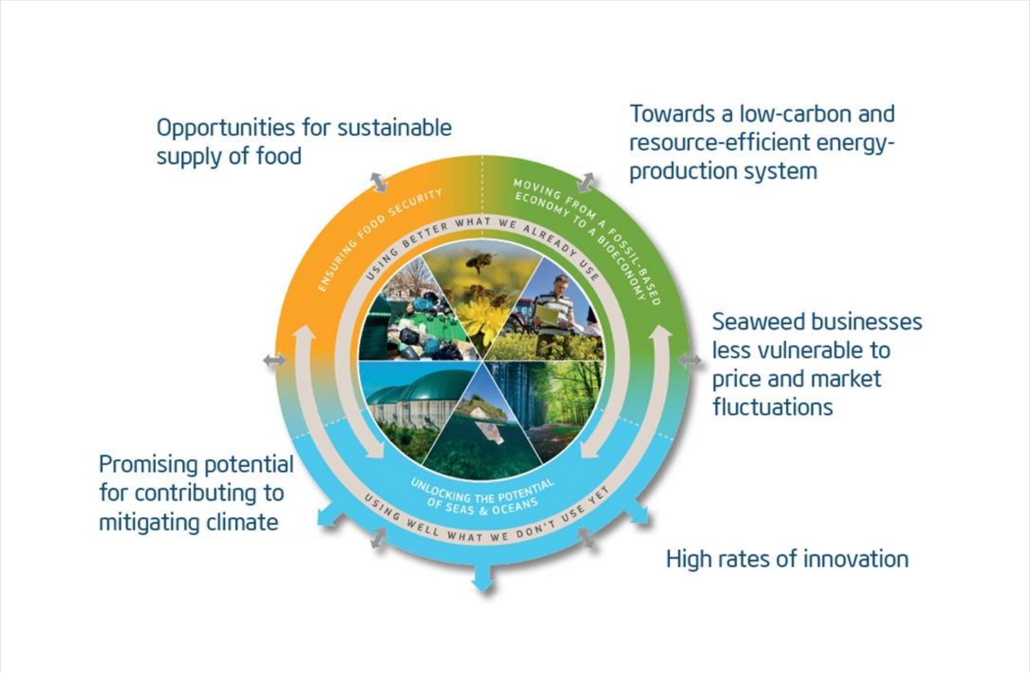


Fig. 7: Agenda for the European bioeconomy and how seaweed aquaculture fits to the overall strategy.

Photo credit: Josh Spires from Unsplash

Seaweed-related patent applications increased at a rate of 11% year^{-1} since 1990 (seaweed-derived products).
Marine biotech revenues in Europe could reach €1 billion within 5 years (i.e. 2024) **if a market growth of 6-8% per year is maintained.**
This would result in the creation of 10,000 new jobs in Europe.
(Marine Biotechnology ERA NET, 2016).

III.2.1 ENSURING FOOD AND NUTRITION SECURITY

The Strategy and Action plans aim to promote the development of a long-term sustainable and safe food-supply system to face the growing global food demand. Several ongoing initiatives contribute to this objective, such as the EU Research & innovation policy framework FOOD 2030, building on four priorities: Nutrition for sustainable and healthy diets; Climate-smart and environmentally sustainable food systems; Circular and resource-efficient food systems; and Innovation and empowerment of communities. For the marine environment, the EC High Level Group for Scientific Advice investigates the opportunities for sustainable supply of food and biomass from marine sources required to support the EU's ocean governance and Blue Economy strategies as well as FOOD 2030 *(See Chapter VI on Challenges on Food safety).*

III.2.2. SUSTAINABLE MANAGEMENT OF NATURAL RESOURCES

The Strategy and Action Plans aim to simultaneously support the increase in production and use of biomass for various applications and sometimes competing purposes, and the protection of ecosystems and the services they provide, thus ensuring the sustainability of the methods of exploitation.

Seascapes are increasingly managed for multiple functions and services in addition to the provision of food, and this requires the integration of ecological and socioeconomic research, policy innovation, and public education. The multi-use dilemma has driven many researchers, experts, and policymakers to try and address issues relating to the sustainability of coastal development from disciplinary/sectoral perspectives addressing the interactions and functioning within the wider ecosystem, social, economic, and political contexts (Buchholz et al. 2012). A review by Harley et al. (2012) addressed the significant gaps in understanding, which hamper an ability to predict the outcomes of global change in seaweed-dominated systems. In particular, it indicated the lack of general or even basic understanding of: *(i)* the importance of rates, timing, magnitude, and duration of environmental change; *(ii)* non-additive effects of multiple stressors; *(iii)* population-level implications of variable environmental impacts among life-history stages; *(iv)* the scope for population- or species-level adaptation to environmental change; and *(v)* ecological responses at the level of communities and ecosystems, including tipping points and sudden phase shifts. In this regard, biological (i.e. ecophysiological) responses to key environmental drivers or combinations of drivers can be incorporated into demographic models to better describe and predict changes in the growth or decline of populations. The expansion of seaweed cultivation, particularly in tropical regions, contributes significantly to carbon sequestration given the rapid turnover in seaweed culture, approximately 3 months per crop (in the tropics) with yields of over 2,500 wet tons ha^{-1} (De Silva & Soto 2009; Vásquez et al. 2014). Nevertheless, some authors have pointed out that a significant proportion (estimates range up to 60%) of the carbon they fix photosynthetically is released into the water, and a proportion of this released dissolved organic carbon (DOC) is highly labile, entering in the bacterial loop and rapidly remineralising back to CO_2 (Hughes et al. 2012). Environmental impacts of seaweed farming in the tropics have been reviewed by Zemke-White & Smith (2006). Some authors have also pointed out other environmental impacts of algal farming, both positive (i.e. increase in fish assemblages, Bergman et al. 2002) and/or negative (i.e. effect on the meiobenthos, Olafsson et al. 1995).

All of these impacts should be considered when the environmental effects of seaweed aquaculture are taken into account. The concept of ecosystem-based management approaches based on an integrated approach to the entire ecosystem, including humans, should also be considered to develop coastal spatial planning and the best-practice guidelines for exploitation of seaweed (both harvesting and aquaculture) in order to avoid spatial and temporal mismatches of the governance (Crowder & Norse 2008) (For review, see Rebours et al. 2014). In France, recommendations have been provided by a past project (Netalgae, Figure 8) while in Scotland, the first policy guidelines for sustainable seaweed cultivation are available since 2017.

SEAWEED INDUSTRY IN EUROPE:
A GUIDE TO BETTER PRACTICE
AN OUTPUT OF THE NETALGAE PROJECT
WWW.NETALGAE.EU

netalgae

Netalgae general recommendations for seaweed harvesting in Europe

To ensure the sustainability of algae resources and harvesting activities, the total amount of seaweed harvested should be set in accordance with the availability of wild seaweed resources.

The harvesting techniques employed must be those that offer a low impact on the ecosystem and are adapted to the species biology (to encourage regeneration of resources post removal).

In order to improve the likelihood of resource sustainability it is recommended that some species be cut at a certain size defined by scientists and according to species biology. For some species, the use of ripping as a means of harvesting may be authorised.

Impact assessment of the harvesting activity should be made not only on the target species but also on the associated communities.

Fig. 8: Netalgae general recommendations for seaweed harvesting in Europe.

III.2.3. CREATION OF ECONOMIC GROWTH AND JOBS IN COASTAL AREAS

For most coastal communities in Europe, seaweeds are still a much under-exploited renewable resource. In the context of marine fish depletion, seaweed aquaculture offers the opportunity to set up new integrated industrial sectors with local stakeholders, either through integration of existing aquaculture and processing industries or through the creation of entirely new businesses. In contrast with most examples of aquaculture production (e.g. fish, shellfish) which are solely for the food market, there exists a diversity of markets for selected seaweeds and extracts of seaweeds, i.e fine food (phycogastronomy), food ingredients, animal feed and supplements as well as medical, cosmetic, nutraceutical, pharmaceutical, biomaterials and energy, etc. (Pimentel et al. 2017; Cardoso et al. 2014; Gade et al. 2013; Smit 2004). This diversity in market categories predominates in different regions around the world (Figure 9) and should make seaweed businesses less vulnerable to price and market fluctuations. The seaweed industry is also presently associated with high rates of innovation, in the form of new processing methods or products.

The benefits for the wellbeing of coastal communities, such as an increase in direct, permanent employment in previously disadvantaged coastal communities (where unemployment is not only an economic issue but also a sociopolitical concern) have been exemplified by an IMTA farm of abalone and seaweed in South Africa (Nobre et al. 2010). Sustainable management of coastal resources creates new economic activities based on the exploitation of a given raw material and could participate in local socioeconomic development in coastal areas and communities. Developing long-term management plans will also produce fundamental long-term results of interest to the international research community. Socioeconomic benefits derived from seaweeds have been already observed in the Philippines where approximately 116,000 families comprising approximately one million individuals farmed more than 58,000 ha of seaweed, making seaweed farming the largest and most productive form of livelihood among the coastal population. In Zanzibar (Tanzania), more than 90% of seaweed farmers are women. As in Latin America, life changing opportunities are provided thereby giving women the means to gain independent economic power. As a first step, this contributed to the reduction of childhood malnutrition (as an indicator of mother's health improvement), and to the increase in child education, thereby reversing the trend of rural depopulation through the self-employment of village youths (Msuya 2006; Msuya et al. 2007). However, seaweed aquaculture might be further facilitated through improvement of cultivated strains, equipment and culture conditions.

Innovation should be promoted when trying to integrate seaweed harvesting or aquaculture as part of the wealth of coastal communities. In this regard, Castellacci (2010) pointed out that the technology dynamics of a country depend on three main factors: its innovative intensity, its human capital, and its technological infrastructures. In order to close the gap and eventually jump to the innovation-development stage, developing economies should implement an appropriate combination of policies that take into account the need to simultaneously develop R & D activities, traditional infrastructures, information and communication technologies, and advanced human skills. Human-capital education explains differences in economic performance across countries; education is, therefore, a necessity to promote social inclusion and cohesion as well as employment. By focusing on marine resources with low-cost technology requirements, such as the production of seaweed, countries are provided an opportunity to access an emerging market, propelled by a diversification of demands for products from various seaweeds, from their traditional uses to bioenergy, cosmetics, and bio-medical applications. (For review, see Rebours et al. 2014).

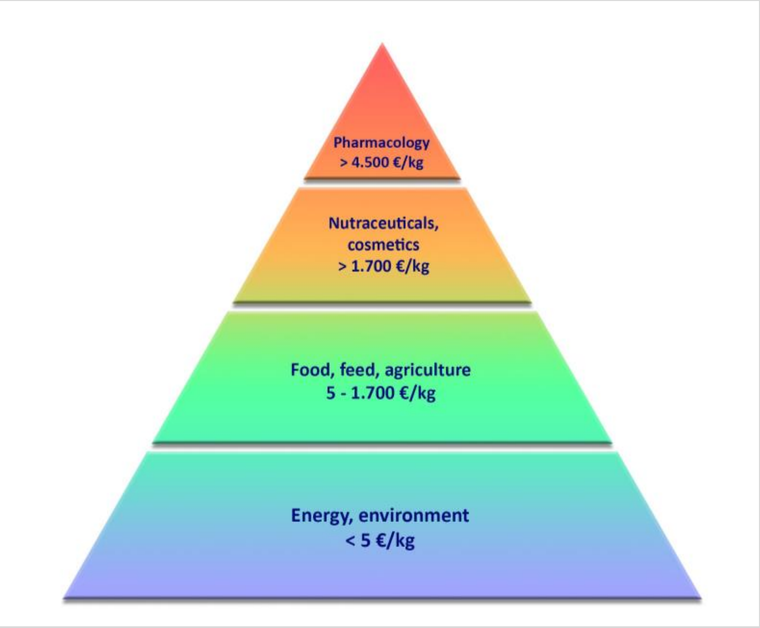


Fig. 9: The volume/profit pyramid value for marine biotechnology domains (adapted from Day et al. 2016).

III.2.4. REDUCE FOSSIL FUEL DEPENDENCE, INCREASE CIRCULARITY AND RESOURCE EFFICIENCY

The European Commission defines the Circular Economy as an economic system in which the value of products, materials and resources is maximised and the generation of waste reduced by optimising the valorisation pathway, to increase energy efficiency and reduce emissions. The recent developments in bioenergy production target a transition towards a low-carbon and resource-efficient energy-production system, promoting the use of renewable energy (which includes biofuels) as an alternative to fossil-fuel-based energy. In such a context, biomass energy from macroalgae (methanol) has also been suggested as a replacement for petroleum-based energy (Goh & Lee 2010).

Since seaweed cultivation is the form of aquaculture with the least environmental impact, it is expected to improve the social acceptance of coastal aquaculture. It also provides several environmental services (i.e. absorption and storage of CO_2 and nitrogen, buffering of local ocean acidification, and lowering eutrophication; *(see Chapter I on Seaweeds as an opportunity to meet human needs)* that improve the quality of coastal waters, with positive benefits for local communities and industries.

III.2.5. MITIGATING AND ADAPTING TO CLIMATE CHANGE

The temperatures in the Atlantic water masses in the Barents Sea have recorded a strong positive trend over the last 40 years. This accelerated in the late 1990s (Lind et al. 2012). The increase of atmospheric CO_2 and reduction in the pH of marine waters are cause for concern because of their regulation of the closely interlinked relationships between microorganisms, plants and animals. Changes to any of these components may lead to the destruction of large deep-water coral and coralline algae reefs, which, taken together, are important ecological actors in the European waters. Climate change also appears to cause the introduction, establishment and expansion of several non-native and tropical species (Verlaque 2005; Wallentinus 2002; Anderson 2007; Schaffelke & Hewitt 2007). The introduction of alien species and species extinction are considered major threats to biodiversity and ecosystem services (Boudouresque 2005; Occhipinti-Ambrogi 2006; www.artsdatabanken.no; Cottier-Cook et al. 2017).

Climate change is likely to impose threats to marine ecosystems and consequently aquaculture, while such changes also provide innovative opportunities in the aquaculture industry. Recent evidence has shown that several species are changing in distribution and abundance as a result of an increase in environmental pressures such as global warming. Knowledge and technologies currently developed are expected to support the adaptation of the agriculture, forestry and maritime sectors to climate change (Duarte et al. 2017). Iodine vapours released from some brown macroalgae condense to form aerosol particles over oceans. These aerosols have a significant impact on climate change as well as on precipitation patterns, as aerosols work in an opposite manner to greenhouse gases (O'Dowd et al. 2002).

However, seaweeds and their cultivation have shown promising potential for contributing to mitigating climate change as they absorb massive quantities of CO_2 (Duarte et al. 2007). For example, the Norwegian kelp forest can fix 1000 g C m^{-2} y^{-1} (Fredriksen 2003).

Finally, as also previously noted, some authors have pointed out that a significant proportion of carbon photosynthetically fixed by algae is released into the water, with a proportion of this released dissolved organic carbon entering in the bacterial loop and rapidly remineralising back to CO_2 (Hughes et al. 2012).

III.2.6. IMPROVED ECONOMIC AND ENVIRONMENTAL SUSTAINABILITY, THE COMPETITIVENESS OF PRIMARY PRODUCTION AND PROCESSING INDUSTRIES, AND CREATE JOBS

Worldwide, the demand for elaborated and value-added products from macroalgae is increasing, however, seaweeds are seldom used in Europe outside of the alginate industry (Meland & Rebours 2012b), despite the significant biomass (Steen 2009). Seaweeds are however a key biomass for the development of a bio-based economy as they can contain much needed constituents such as proteins, sugars, nitrogen, phosphorus, and can therefore be utilised as feedstock (Seghetta et al. 2016). There seems to be two key reasons for the lack of development in Europe.

Firstly, for seaweeds used for high-end markets such as ingredients for cosmetics and restaurants, heavy-metal regulations are perhaps the biggest hurdle because these impose an artificially low limit for what is perceived as safe consumption. Regulations in some countries do not distinguish between organic and inorganic heavy-metal compounds such as arsenic and cadmium, which can be found in some seaweeds. This creates unnecessary health debates over the appropriateness of eating seaweed or using it as feed for animals. The consumption of seaweeds in China, for example, is many times higher than that of the EU, but there are no detectable negative health effects. The reason is that most of the heavy metals in seaweed are organic and therefore harmless for humans – but this understanding is not taken into account in EU regulations today, making their amendment necessary *(see Chapter VI on Challenges in Food safety).*

Secondly, considering industry in the EU, the primary production or processing of seaweeds is at a very low level. This greatly reduces the competitiveness of seaweed for animal feeds and supplements, as this sector competes against much large-scale products such as soy protein concentrate (SPC). SPC, in fact, has significant, negative environmental effects as large areas of rainforest in South America have been cleared to grow soya. In contrast, various seaweeds can be produced in the world's oceans and the potential areas suitable for their cultivation are heavily under-utilized. Here is therefore an argument for having seaweed products displace ingredients such as SPC in animal feeds and supplements. However, the European and global seaweed industries must scale-up to having the capacity and facilities to produce around 100,000 - 300,000 tons per year. This is the scale SPC is based on, and since these types of products are commodities, a similar scale would be required for seaweed processing in order to meet the price levels of soya (Emblemsvåg et al., in preparation).

In addition, Philis et al. (2018) reported on a comparison made between the primary energy and phosphorus demands for the production of 1 ton of soy protein concentrate, as opposed to 2 tons of seaweed protein concentrate (i.e. commodities with similar protein content). The primary energy consumption of the latter protein source (i.e. 172,133 MJ) was calculated as 11.68 times larger than that required for the soy-based concentrate (i.e. 14,733 MJ). However, the seaweed protein energy requirement could be reduced to 34,010 MJ, if secondary heat from a local waste-incineration plant was used to dry the biomass during the late-spring harvest. Meanwhile, the seaweed system outperforms the soy system regarding mineral phosphorus consumption since 1 ton of soy protein requires 25.75 kg mineral phosphorus while 1 ton of seaweed protein requires as little as 0.004 kg input. These results indicated that substituting soy protein with seaweed protein in aquafeed leads to an environmental trade-off.

The value-chain of selected seaweeds produces proteins with near-zero mineral phosphorus consumption using naturally-occurring marine phosphorus. Therefore, the soy value-chain produces proteins for roughly one twelfth of the primary energy required by seaweed. Based on current production technology, the seaweed value-chain will require extensive innovation and economies-of-scale to become competitive in terms of energy. Further research should investigate the predictive environmental impacts of a fully developed seaweed protein concentrate value-chain and account for the background emissions and multi-functionality of each system.

Regulatory issues in Europe must be addressed as they greatly hamper further use of seaweeds at a large scale.

The EU bioeconomy employed around 18.6 million people in 2014 and generated approximately €2.2 trillion, making an important contribution to the EU economy. With responses to the suggestions made above, there is no reason to doubt that an industry based on selected seaweeds could double, if not triple, in size in relatively few years. R&I funding has increased to stimulate knowledge about the production and development of technologies to support greater competitiveness and job generation in various sectors of the European bioeconomy. An example is the Rural Renaissance Action Line in the EC's Societal Challenge 2 which has stimulated the development of bio-based business models suitable for adoption by rural actors. However, the aforementioned regulatory issues must also be addressed because they greatly hamper the further use of seaweeds at a large scale.

III.2.7. CONTEXT OF THE IMPORTANCE OF ALGAL RESOURCES FOR EU POLICIES

European experts should therefore collaborate to develop guidelines in order to plan integrated coastal management strategies for European seaweed resources. It is also of foremost importance, to establish legitimacy, that such guidelines should originate from trans-national and cross-sectorial co-operation, including political, cultural, commercial and industrial actors, NGOs, and research communities. Algae are important resources for the implementation of the EU's environmental and bio-based targets. The sustainable development of algal biomass production contributes to the implementation of EU strategies on Blue Growth, the Bioeconomy, Circular Economy and Maritime Spatial Planning. Additionally, the environmental protection of macrophyte communities is an important criterion for the achievement of good environmental status for coastal and open-sea waters under the Water Framework

Directive and the Marine Strategy Framework Directive. The EU intends to promote the aquaculture sector through the Common Fisheries Policy reform and the Blue Growth Strategy, for which algae represent a source of high added-value chemicals and bioactive compounds. The development of the industrial algal sector will also contribute to the objectives of the EU strategies by promoting sustainable growth and creating jobs in the bioeconomy, marine and maritime sectors.

Seaweed utilisation, an increasing economic value

Biomass exploitation

✓ Texturising agents: carrageenan, agar-agar, alginates.

✓ Food and supplements rich in protein, low in fat, rich in oligoelements and dietary fibres.

✓ Feed ingredients, fertilisers, ersatz plastic, pharmaceuticals, cosmetics, nutraceuticals, biofuels.

Environmental benefits

✓ Capture of CO_2 and inorganic waste products.

✓ Higher yield compared to land cultivation.

✓ No need for freshwater for growth pf the biomass.

Ecosystem services

✓ Coastal ecosystem services.

✓ Erosion (€5.4 B y^{-1} in EU – 1990-2020).

✓ Carbon sequestration.

CHAPTER III –

SEAWEED PRODUCTION - CULTIVATION

Coordination: Bertrand Jacquemin (PhD), Centre d'Etude et de Valorisation des Algues, CEVA, France

As is the case for terrestrial plants, there are relatively few seaweeds used in the sector of food applications, as compared to the total number of species. Many interesting seaweed species are not currently used due to a lack of regulatory frameworks and knowledge relating to the technical issues (e.g. cultivation technology and industrialisation of these technologies) associated with the exploitation of new species for food, feed or even cosmetics.

As in the case of agriculture 8,000 years ago, seaweed cultivation generally begins with the harvesting of wild individuals so as to obtain propagules (seeds) or individuals from which the structure or culture material will be sown. Domestication is an intermediate and overlapping process (Figure 10) between the direct, sustainable exploitation of wild resources and agriculture/aquaculture (Valero et al. 2017). In this way, domestication begins as soon as the reproduction and dispersal of a species are linked to human activity (Milla et al. 2015). Domestication is also based on the controls of various life cycles through sexual reproduction or vegetative propagation. However, the diversity and complexity of seaweed life cycles explains why domestication is still in its infancy (especially in Europe) and its production is still much dependent on wild resources.

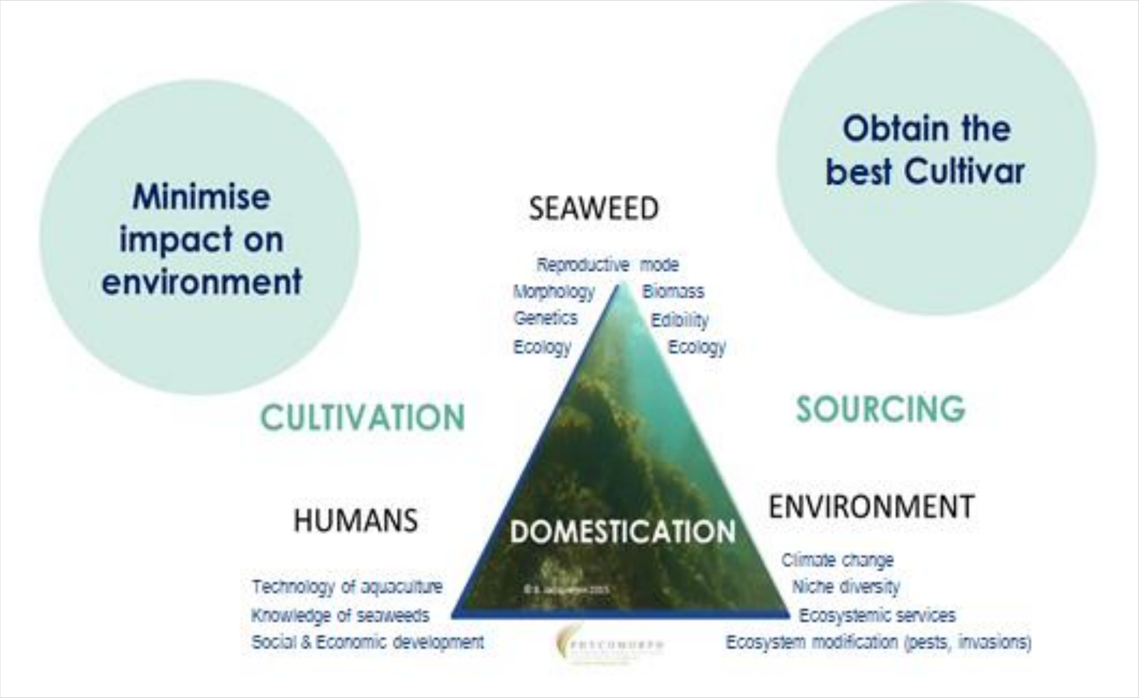


Fig. 10: Factors affecting the domestication process of selected seaweeds (adapted from Valero et al. 2017).

Once a species is domesticated and produced in mass/large volume, domestication has a significant effect on the diversity of associated organisms (symbionts, pests, diseases, etc.) and the structure of the marine ecosystem. This potential impact requires further research. Recent work shows also that the domestication process affects not only the evolution of target species, but also human selection (Valero et al. 2017). A good example is described by the work of Hehemann et al. (2010) which revealed that Japanese populations host a selected bacterium that confers greater digestive capacity of certain seaweed compounds. Further research is required to understand the potential impacts on other species and their environment as well as the long term consequences.

Based on terrestrial agricultural practices, it is anticipated that the upscaling of seaweed aquaculture will require improvement of *i)* the cultivated strains, and *ii)* the associated technical methods. From the producer's perspective, sustainable seaweed aquaculture would theoretically supply the market while reducing the environmental impact of the production process (Figure 11). The choice of the best cultivar depends both on the genetic determinism of traits and on the cultivation process. As the market demand is increasing and still relying on wild natural resource, the extension of the volume tends to be limited in quality and quantity. As a consequence, producers will soon be faced with the problem of answering the demand and supply the market in steady quantity of algae of stable quality.

To develop a sustainable seaweed aquaculture, the above three interlinked questions would need to be answer:

a) What are the characteristic and the origin of the species being cultivated (wild populations or selected cultivars strains)?

b) What cultivation methods and facilities are/should be used?

c) Why and for which market and at which volume and quality, are these species are selected for cultivation?

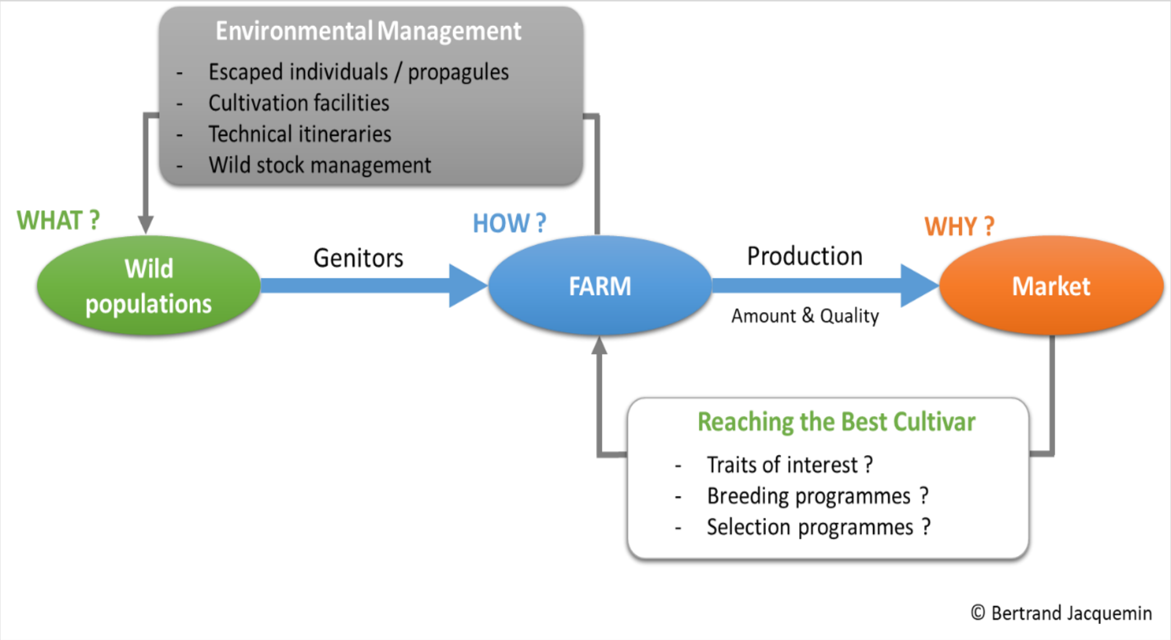


Fig. 11: Different questions that should be asked and answered when developing a seaweed-aquaculture farm (© Bertrand Jacquemin, CEVA).

I - SOURCING

The term "sourcing" refers to the acquisition of raw materials used in a given process. In this way, the "sourcing" of a seaweed farmer corresponds to the biological material from which the crop is developed. However, for the industry which values the biomass produced, sourcing represents either the form in which this biomass will be used or the search for and the evaluation of a supplier able to satisfy an identified need.

I.1. Origin of cultivated strains

I.1.1 NON-INDIGENOUS SPECIES

Non-indigenous or introduced species are those which occur outside their native natural range and have been introduced directly or indirectly as a result of human activity that is either intentional (i.e. for cultivation) or unintentional ((i.e. a vector which is associated with another cultivated organism, vessel, traffic, etc). In the case of seaweed aquaculture, a non-native species is only cultivable if it is genetically adaptable to the local environment of the farm.

Proportion of introduced species will tend to establish and spread beyond the place of introduction. These are considered invasive if they hurt native species and ecosystems. The term "invasive" is limited to species that have been reported to cause economic or ecological damage to coastal ecosystems. A third term, "cryptogenic species" refers to those whose region of origin is uncertain (Carlton 1996). Surprisingly, the term cryptogenic applies to the majority of seaweeds and several populations are still reported to not have yet reach equilibrium.

> *“Whether consequence or cause of global change, the expansion range of exotic species depends on defying the barriers of natural dispersal and on adaptation to a novel local abiotic and biotic environment in which the organism did not evolve.”* Voisin et al. 2005

The combination of a limited set of morphological characteristics and the associated diagnosis (the "low morphology problem"; Van Oppen et al. 1996), and the very high morphological plasticity that characterises many algal species lead to great uncertainty about the native or non-native status of particular species. Even, the reduced genetic diversity of non-indigenous populations may not be as common as previously assumed (Roman & Darling 2007).

I.1.2 INDIGENOUS SPECIES: LOCAL VERSUS DISTANT POPULATIONS

The marine environment is heterogeneous, conditions i.e. temperature, light, exposure to waves and currents, etc.) can vary greatly on a small scale (a few metres or centimetres). In this way, for each species, the distribution of its different populations is strongly correlated to ecological needs and tolerance. Each species is, therefore, represented by several populations more or less related to each other by physical barriers, dispersal and the species’ reproductive processes.

Also, each population of the same species may be exposed to different environmental conditions and so be exposed to different natural selection criteria. Within a species, seaweed populations can, therefore, be adapted locally to their specific environment and have specific morphological, phenological (Jacquemin et al. 2016) and genetic (Guzinski et al. 2016) characteristics (Figures 12 and 13).

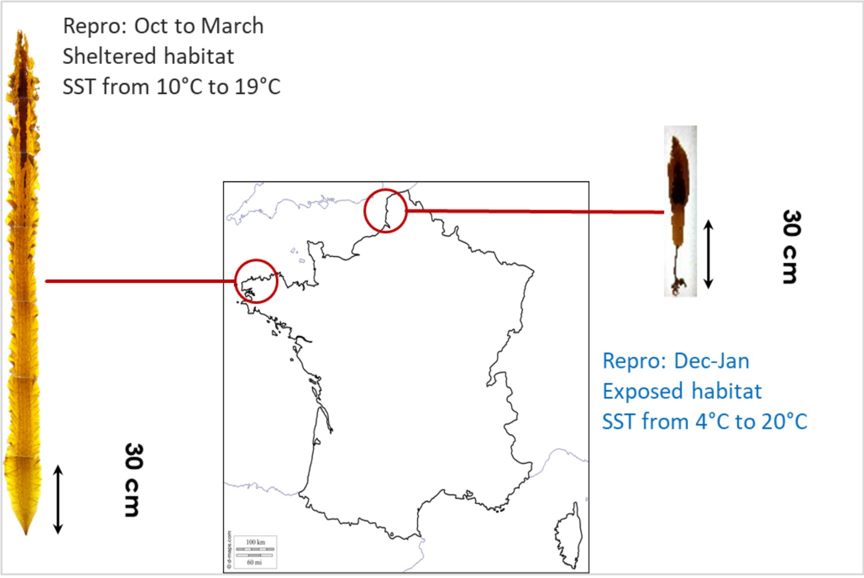


Fig. 12: Population of the kelp Saccharina latissima *with different reproductive periods, morphologies and genetic structures (Jacquemin et al. 2016).*

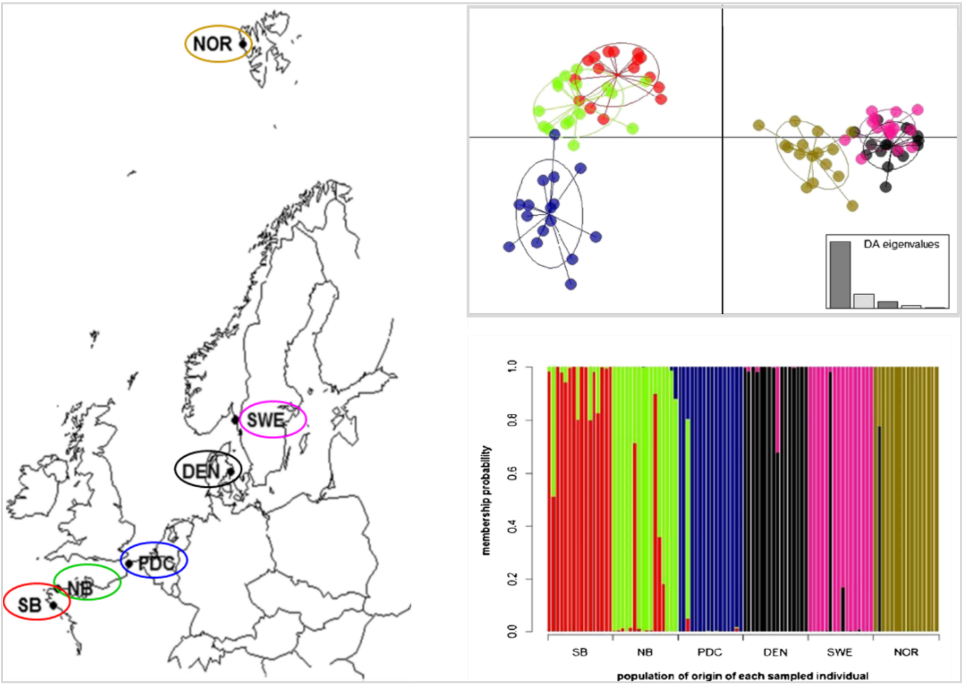


Fig. 13: The kelp Saccharina latissima *populations with low connections and high levels of genetic differentiation. These observations are probably due to local adaptation to environment. (Guzinski et al. 2016). N.B.: DNA markers have been compared between individuals from different populations (identified by different colours). The analysis ran for each individual (sequence) taken randomly from the pool of sequences and assigned to one population with the highest probability of confidence.*

A population is a group of individuals belonging to the same species, reproducing mainly between themselves, occupying a common geographical area and playing a particular role in the ecosystem (Odum 1971).

I.2. Selection of traits of interest and improvement of strains

The commercial application of a given seaweed depends on its properties, including its nutritional value, sugar and protein content, and more generally, its usage as feedstock. The traits of interest (ToI) are related to a phenotype that is the combined effect of gene expression and the environment. Selection refers to the choice of the "best individual" who holds the expected value for the trait of interest.

Traits usually relate to biomass production and quality:

- **High yields**
- **Specific shape/size, texture, colour, flavour, etc.**
- **High growth rates/fast transition between lifecycle stages**
- **High amount of specific target compound (protein, pigments, lipids, iodine, etc.)**
- **Resistance to infection by pathogens or epiphytes**
- **Resilience to changing abiotic factors**
- **Low accumulation of contaminants (e.g. cadmium, inorganic arsenic, etc.)**
- **High nutrient uptake rates**
- **Low emission of halocarbon**

While selection programmes for cultivated strains are well developed for terrestrial plants, cultivated seaweeds are mainly obtained from fertile wild individuals. These local wild populations naturally produce individuals that are well adapted to the local environment and, therefore, to the existing local growing conditions. Selection thus begins from wild individuals and production must be developed locally until the population structure intra and extra species is well understood.

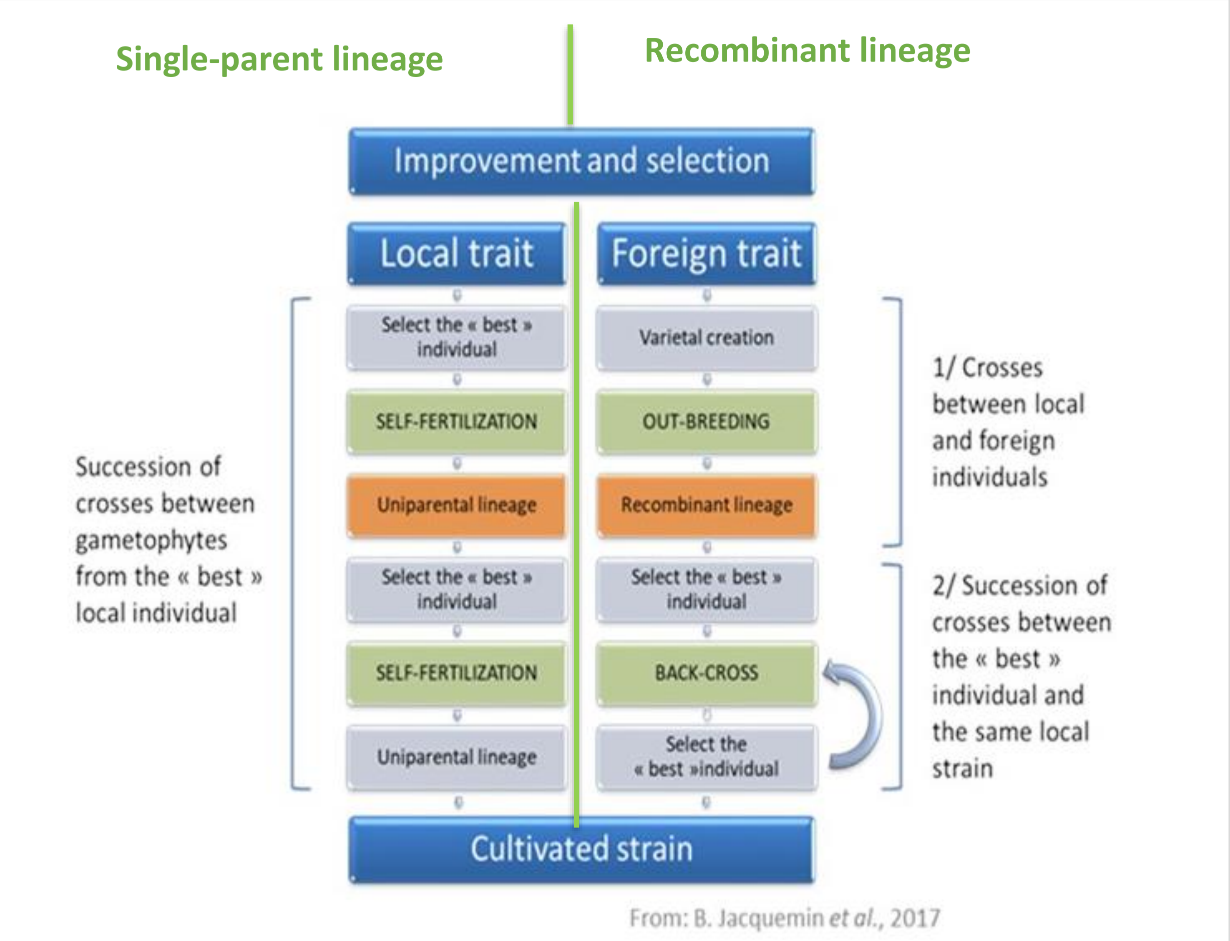
One first step to undertake prior to the start of any selection programme is to identify the determinism of the ToI: from 100% genetic-dependent to 100% environment-dependent, many phenotypic variants are the fruit of a combination of genetic diversity (alleles) and phenotypic plasticity (i.e. different gene expressions in different environments) through epigenetic mechanisms (modification of genetic expression without DNA sequence alteration).

It is therefore important to consider the origin (local or foreign) of the ToI: when a farmer begins a cultivation process by harvesting fertile individuals from local wild populations, the expected value of the ToI may or may not be present under the farm's specific conditions.

I.3. Improvement of strains

Within the last 100 years of agricultural history, 75% of plant diversity has been lost due to farmers choosing to produce high-yielding crops, 30% of livestock breeds have fallen at risk of extinction, and six breeds are lost each month; 75% of the world's food is generated from only twelve plants and five animal species. Among the 300,000-known edible-plant species, only 220 are used and only three contribute to 60% of calories/proteins (FAO 2009). In this context, mitigation of intensive inbreeding is a solution to prevent the loss of genetic biodiversity. Establishing and maintaining strain collections is an additional approach which must be developed in parallel. There are multiple reasons for this concentrated food production from a few species, from natural conditions for food security to consumer choices. To secure genetic diversity, also for breeding purposes and other future interests, seed banks keep a substantial collection of genotypes in temperature and light controlled conditions for seed quality, as in the Roscoff Culture Collection, the Scottish Association for Marine Science and Svalbard Global Seed Vault.

When the ToI is shown to be mainly genetically based meaning that the impact of the environment on gene expression is minimal, then it can be exploited through genetic approaches involving crosses between individuals with ToI. If the ToI is characterised from a local strain, then the approach will consist in stabilising it in this genetic background through repetitive crosses (also named "self-fertilisation", Figure 14, left side). However, if the ToI is characterised from a geographically distant strain (usually also genetically distant), then the approach first requires the introduction of the ToI in the local strain, and then its stabilisation by repetitive crosses (Figure 14, right side).



From: B. Jacquemin *et al.*, 2017

Fig. 14: Description of the process for improving the strain by use of single-parent lineage or recombinant lineage. Selection programmes for improved strains can be based on either a clonal line, a single-parent line or a recombinant line:

- *Clonal line: vegetative propagation of a selected individual.*
- *Uniparental lineage (self-fertilisation) of an individual holding the expected ToI in the expected genetic context.*
- *Recombinant lineage: crosses between different individuals.*

(© Bertrand Jacquemin, CEVA)

Examples of both processes to produce potential efficient cultivars can be found in the literature for different cultivated seaweed species like *Undaria pinnatifida* (Shan et al. 2016), *Saccharina japonica* (Zhang et al. 2018) or *Macrocystis pyrifera* (Camus et al. 2018).

The crossing of two distinct strains entails either inbreeding or outbreeding. Inbreeding consists of crossing parents originating from the same population and will result in establishing a local character in the local genetic background. Outbreeding consists of crossing parents from different populations and will result in the introduction of a foreign character into the local genetic background.

Outbreeding or inbreeding techniques, therefore, have different impacts on a genetic level as they result in mixing DNA of high or low similarity (Figure 15, top). Consequently, these two techniques can cause a loss of genetic potential, called genetic depression (Figure 15, bottom). As such, inbreeding and outbreeding can have a real impact on the quality of the cultivated strain or on the stability of the biodiversity.

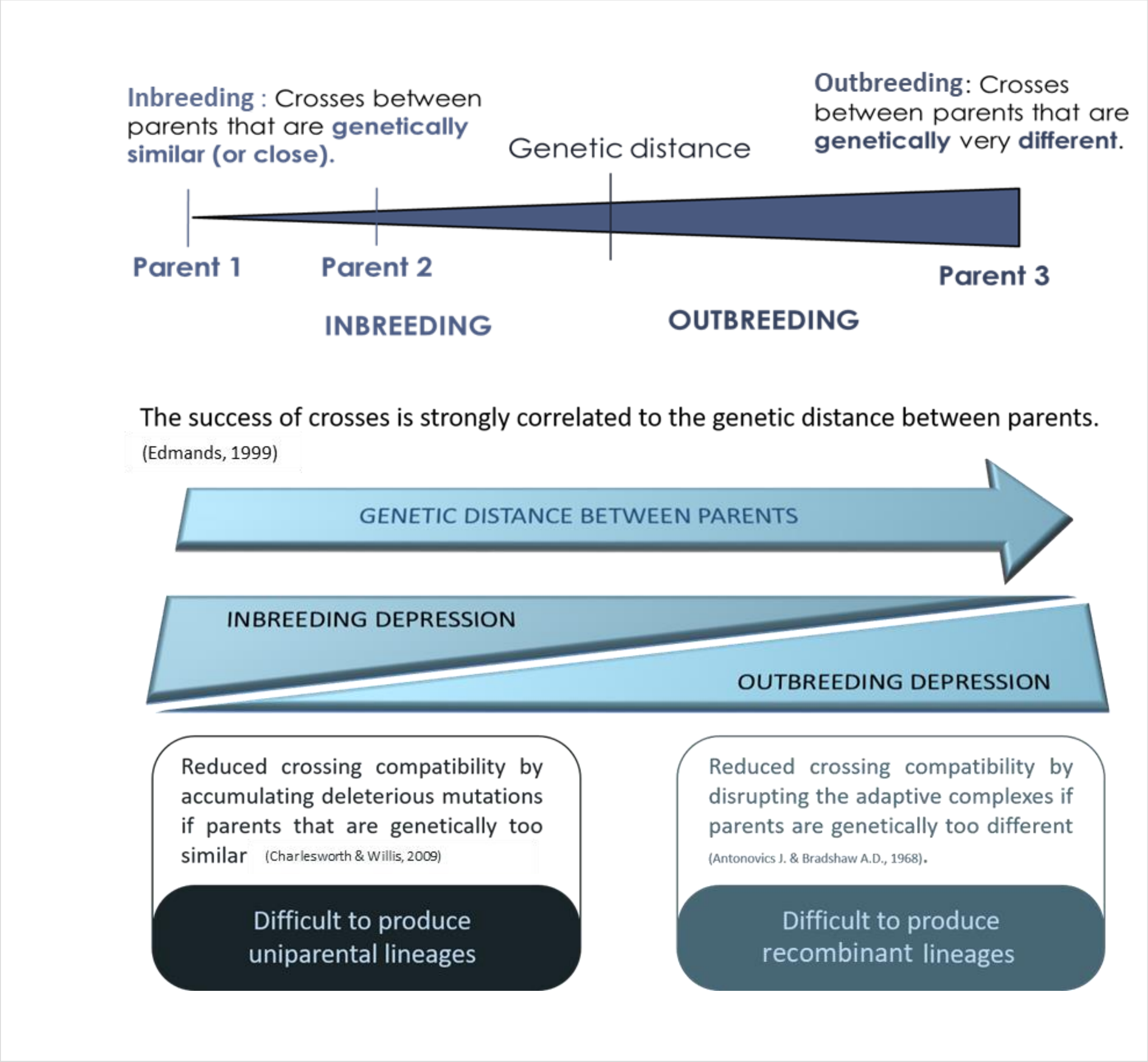


Fig. 15: Top: Definition of inbreeding and outbreeding as a function of genetic distance. Bottom: Risk of genetic depression as a result of inbreeding or outbreeding (© Bertrand Jacquemin, CEVA).

I.4. Strain collections

The principle of strain collections is to store living organisms of interest for long periods.

I.4.1. STRAIN SELECTION

Isolation of native strains should be encouraged in particular because of the possibility of building ecotypes along the long and diverse European coastline (Orfanidis & Breeman 1999). Knowledge of several factors such as temperature, nutrients, salinity and light defining the environment in which the species/ecotype grows are needed to identify optimal conditions for growth, biochemical composition or flavour per unit of time, effort and cost (Hurtado et al. 2013). In addition, for rapid screening of strains with superior growth performance and resistance qualities, chlorophyll fluorometry under biotic and abiotic stress (dark or light-adapted protocols) and visible and near infrared (NIR) spectroscopy could be used.

I.4.2. STRAIN STORAGE

Seaweed strains can be stored in two methods:

- The vegetative culture of individuals in the microscopic or macroscopic stages of their life cycles. Cultivation conditions must be defined and controlled as no breeding events are allowed during this storage period in order to keep the culture close to its original stage. For example, in the case of kelp species, male and female gametophytes are grown under conditions where fertility is blocked. As such the Spanish Institute of Oceanography (IEO) has been setting up gametophyte stock cultures (genetic-material bank) of *S. latissima* and *U. pinnatifida* from Iberian populations at their southern limits of distribution (Barrento et al. 2016) since the 1990s. Another example is the preservation of *Porphyra* species strains by maintaining the conchocelis phase in dormant status.
- Cryopreservation of individuals as commonly performed for animal gametes and embryos. The main challenge of this method is that the preserved cells must be able to recover their growth and fertility when they leave the cryogenic process. These techniques are still being studied for seaweed species (e.g. Barrento et al. 2016; Day 2018). *See chapter VII on Research programmes.*

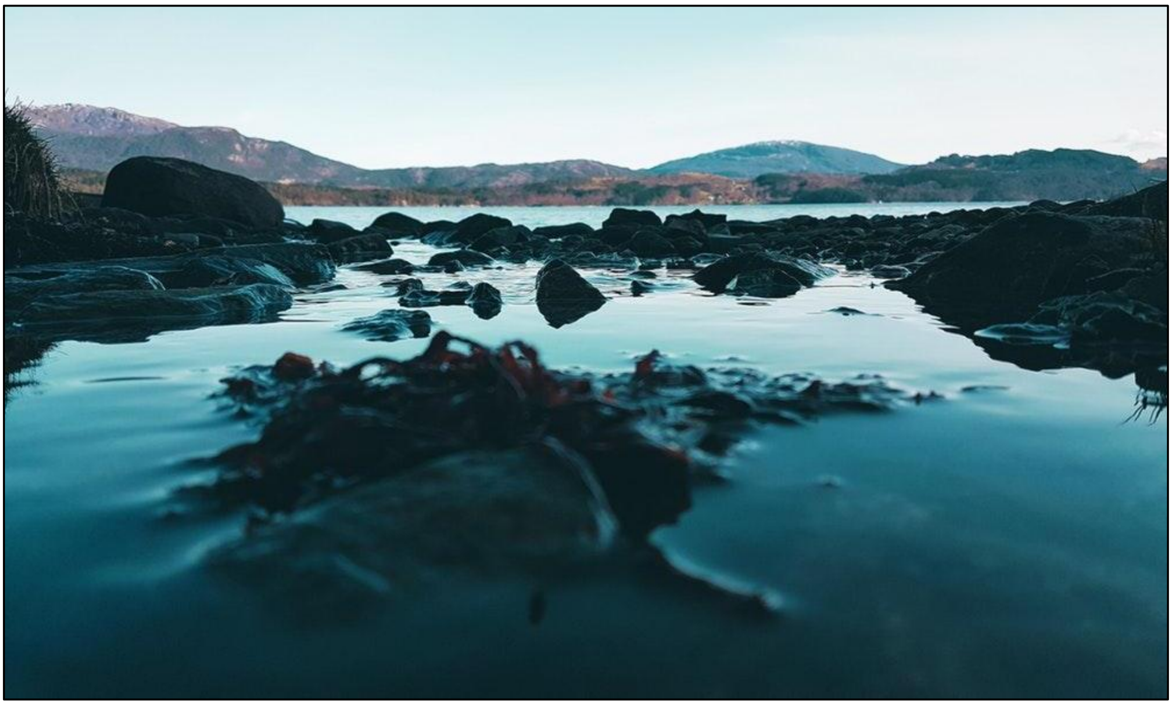


Photo credit: Steffen Mossefinn from Unsplash

II - CULTIVATION TECHNIQUES

In Europe, seaweeds are cultivated in open waters (artificial structures in sheltered coastal areas) or in land-based locations (ponds, artificial tanks or raceway systems). Open-water and land-based farming are suitable for different species and will need to co-exist. For both at-sea and land-based cultivation systems, different methods have been developed based on knowledge about the life cycles of species and the technical applications available to control the progress of different steps. For example, some species (such as kelp) are grown from breeding or other reproduction-based processes while others (such as sea lettuce) are grown throughout vegetative reproduction (i.e. pieces or small plants are grown on farms).

II.1. At-sea systems

In at-sea systems, horizontal or vertical cultivation supports are fixed to a benthic structure. In some cases, long line depths can be adjusted and adapted to different species or growing periods depending on the environmental parameters of the site.

II.1.1 FLOATING CULTIVATION

Floating structures such as buoys or rafts are anchored whereas long lines, textile sheets or nets are fixed near the surface. Kelp is generally grown on long line fishing systems similar to blue mussel aquaculture structures. Spores from mother plants or gametophyte stock cultures (genetic-material banks) are used to produce cord seedlings under controlled environmental conditions in terrestrial facilities ("hatcheries"). Seedling twine is mainly attached to the growing ropes by two methods: the twine is helically wrapped around the growing rope, or a piece of twine is woven at regular intervals into the structure of the growing rope. A new technique is also used in Norway where the gametophyte are directly attached with a natural based glue to the rope on the same these ropes are deployed at sea.

Seaweed substrate lines can be suspended horizontally or vertically from long lines. The optimal growing depth is between 1 and 3-5 meters from the surface. As an alternative to long lines, floating rafts equipped with rearing systems constructed using horizontal ropes (long lines) or suspended ropes (garlands and vertical types) have been tested for commercial-scale seaweed mariculture. Fixed-pole and concrete-block anchoring systems have been used for floating-raft rearing (Peteiro & Freire 2012, 2013a; Peteiro et al. 2014; Peteiro et al. 2016b; Peteiro 2018).
Recent work has tested different 2D systems for kelp production. To illustrate this, the At-Sea consortium (completed in 2015) has developed a 2D textile substrate that produces 3 to 5 times more biomass than the usual long line system. However, due to its large surface area exposed to marine currents and the possibility for other species to settle down on this substrate, its applications are still limited to specific conditions.

II.1.2. BENTHIC CULTIVATION

Benthic culturing is not widely practised, but it is one of many possible options for the concept of "marine forestry/forestation" whereby seaweed cultivation is proposed, primarily to (re)establish biodiversity and to boost the health of the local oceans, by using artificial rifts to recolonise areas that have been devastated by human activity. Marine reforestation is currently actively undertaken in Quebec. Benthic cultivation systems are also used outside Europe for several species such as Nori (*Porphyra spp.*), Aonori (filamentous *Ulva spp.*), *Gracilaria* spp., *Eucheuma* spp. or *Kappaphycus* spp. Long lines, nets or wire mesh are fixed to a structure anchored to substrates.

In Europe, efforts have been made to develop new and innovative structures and artificial substrates to enable high-sea breeding. Neumann et al. (2016) report pilot cultures with almost two-dimensional carrier units suspended vertically from the long line structures, each 6 m wide and 5 m high. However, for current and future crop volumes, the availability of more sheltered prime sites and easier-handling linear rope-based substrates will likely be the standard for brown-algae culture.

II.2. Land-based systems

The production of some marine algae species, mainly due to their size, is potentially more successful when cultivated in land-based systems (e.g. *Chondrus crispus*, *Ulva* spp., *Palmaria palmata*). In this case, the algae float in basins (circular or rectangular) or raceways where the biomass is kept in motion by bottom-aeration or paddle-wheel systems. The optimal height of the tank varies with species in culture but should not be over one meter to ensure sufficient light supply for all individuals.

The advantages of growing on land are: full control over the main production factors (stocking densities, nutrient availability), consistency in yield and quality of the biomass, traceability, the ability to apply stress protocols to optimise the composition of target compounds. Land-based production is also easier to couple with on-site processing.

The disadvantages of these systems include the need for land space, high infrastructure costs and energy expenditure. Possible solutions for these questions are:

i) Rehabilitation of existing and under-utilised infrastructures such as earthen ponds and shellfish storage tanks.
ii) Use of renewable energy to power production and processing systems.
iii) Combine seaweed land-based production with other activity such as fish hatcheries and/or farms.

Land-based seaweed cultivation systems are already found in Canada (company Acadian SeaPlants farming *Chondrus crispus* - ca. 30 000 m^2) and South Africa (Five abalone farms with integrated *Ulva* production. These systems have been described by Ryther et al. (1979) and Bolton et al. (2009). The company ALGAplus (Portugal) has also started producing *Ulva rigida*, *Codium tomentosum*, *Gracilaria gracilis, Porphyra dioica* and *P. umbilicalis* in an organic certified land-based system coupled with a fish-farm.

II.3. Hatcheries

In aquaculture, seaweeds grow on artificial substrates or under free-floating conditions. Regardless of the method of cultivation, land facilities are necessary to accommodate the hatchery units and processing of the biomass. Although most species can be grown through vegetative propagation, the production of juveniles/seedlings is mandatory for several important commercial species like kelp and nori.

For any seaweed species grown through sexual reproduction aquaculture, optimising hatchery production processes is essential to the success of the farming process (mariculture or land-based). In kelp, for example, the deployment of strings with unconsolidated, or smaller, less dense young sporophytes can lead to a significant reduction in yield. Therefore, special attention is given to the conditions under which juveniles are produced in hatcheries (including disease outbreak, see below). Hatchery technology for the large-scale production of *U. pinnatifida* and *S. latissima* individuals attached to strings using gametophyte stock cultures has been developed and tested on several sites in Europe (Ireland, the Netherlands, Norway, Scotland, Spain). Hatchery protocols for the production of two Atlantic nori species (*P. dioica* and *P. umbilicalis*) have been validated in Portugal by the company ALGAplus, with two consecutive years of blade production. Work on these species is also ongoing in France, Denmark, Norway and Scotland.

II.4. Forced cultivation

The cultivation method of *Saccharina japonica* in Asia, called "forced cultivation", is the best mariculture technique for *S. latissima* in northern Spain. "Forced cultivation" allows an earlier growing period during the cold season while reducing the time spent growing at sea, which results in higher yields at lower cost. In addition, the transplanting method using young fronds should be considered as an alternative for subsequent planting or as an option to benefit from the fronds obtained during thinning if it is carried out; this approach should increase both the potential quantity and quality of the harvest. Kelp harvesting can be carried out using several pieces from the largest sporophytes (thinned), but the most recommended method is to harvest all sporophytes from the short growing season with an optimal temperature at their southern distribution limit (Peteiro et al. 2006; Peteiro & Freire 2012, 2013a; Peteiro et al. 2014; Peteiro et al. 2016b).

Clonal propagation of Sea Lettuce (*Ulva* spp.), Ogonori (*Gracilaria gracilis*) and Dead-Man fingers/Velvet horns (*Codium tomentosum*):

- Farming relies solely on asexual reproduction.
- Harvesting frequency changes according to the species and farming site (daily, twice a week or monthly harvests are possible).
- In Southern Europe, the production of these three species can be done year-round (Helena Abreu from Algaplus, *personal communication, 2019*).

II.5. Integrated Multi-Trophic Aquaculture

Integrated multi-trophic aquaculture (IMTA) is the combination of different aquaculture productions (fish, seaweeds, and invertebrates) to take advantage of the trophic relationships between them (Chopin 2006, 2017; Figure 16). This type of cultivation is expected to reduce the environmental impact of each production and diversify farm activities to various markets.

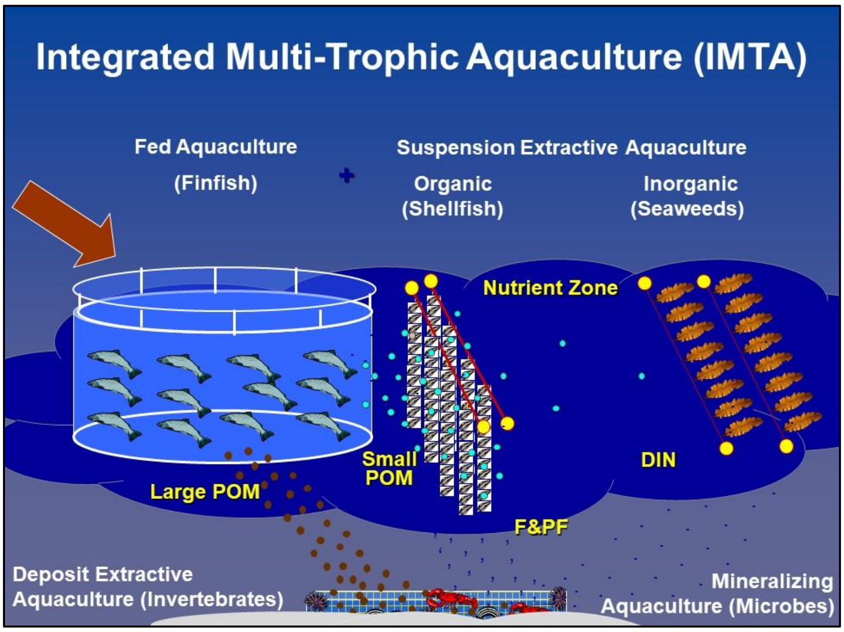


Fig. 16: Exploiting recycling benefits through IMTA at sea (courtesy T. Chopin, from Chopin 2017).

The selected species and system designs are engineered to optimise the recapture of waste products, now considered co-products within a circular economy framework. As larger organic particles like uneaten feed and feces settle down below the cage system, they are eaten by deposit feeders like sea cucumbers and sea urchins. At the same time, fine suspended particles are filtered out of the water column by filter-feeding animals like mussels, oysters and scallops. Seaweeds are placed a little farther away from the site in the direction of water flow, so that they can remove some of the dissolved inorganic nutrients from the water, like nitrogen, phosphorus and carbon. For example, kelps absorb some of the inorganic nutrients produced by mussel and fish aquaculture, thus contributing to reducing their concentration in seawater. This type of culture can be considered as the basis for sustainable aquaculture development (Peteiro et al. 2016b; Peteiro 2018). *S. latissima* is considered one of the most suitable kelp species for incorporation into IMTA systems in temperate cold waters, as it has already been successfully tested in Galicia, northwest Spain (Freitas et al. 2016) and Norway (Stévant et al. 2017c).

A brief history of the IMTA concept

In September 1995, at the conference “Cold Water Aquaculture beyond the Year 2000”, in St. Andrews, New Brunswick, Canada, Thierry Chopin gave a presentation entitled “Mixed, integrated, poly-, or multi-level aquaculture – whatever you call it, it is time to put seaweeds around your cages”.

The hope was to differentiate this practice from “monoculture”. Obviously, the term “polyculture” existed; however, cultivating three species of fish together does not address the issues that arise when co-cultivating three fed species together.

In March 2004, at a workshop in Saint John, New Brunswick, Thierry Chopin was proposing to call this practice “Integrated Aquaculture” and Jack Taylor was mentioning “Multi-Trophic Aquaculture”. They combined the two and that is how “Integrated Multi-Trophic Aquaculture”, or “IMTA”, was born (Chopin *et al*. 2010). To this date, it is interesting and encouraging to note that more than 1,300 publications on IMTA have been published.

It should be recognized that if the “IMTA” acronym is recent, this ancestral method has, in fact, been practiced in different configurations, for a very long time: from 4,000 years ago in China, first in freshwater (integration of fish with aquatic plant and vegetables); to 2,000 years ago in Egypt (Nile tilapia with floating plants and fruit trees); 1,500 years ago in Hawaii with the Ahupua’a agriculture-aquaculture integrated farming systems; and, 400 years ago with the carp ponds developed by Henri IV at the Fontainebleau castle in France.

In the last decades, the concept of IMTA has been developed within consortia integrating research institutions and companies from different countries (e.g. Increasing Industrial Resource Efficiency in European Mariculture - IDREEM project). The purpose was to promote knowledge transfer between academia and industry in order to support the implementation of IMTA systems at commercial scale. For this upscaling to happen, some biological, technical and socioeconomic issues were settled. Examples of major challenges that need further attention are the stabilisation of cultivation methods for seaweed and benthic organisms (biological), structure stability for offshore sites and logistics for deployment and harvest at sea (technical), as well as policy and regulations including licensing and IMTA product certification (socioeconomic) (Alexander et al. 2015).

The integration of seaweed cultivation with other seafood is advantageous not only for nutrient requirements (reduction of fertiliser requirements in seaweed production), but also for sharing processing infrastructures and distribution channels. IMTA is beneficial to seaweed farmers as it saves operating costs and raises the possibility of reaching new customers.

While at the scientific and practical levels, IMTA is an evolving concept, it currently suffers a lack of a contextual frame that would contribute to promote its visibility and development in Europe.

Co-culture in Canada

To illustrate a technique of co-culture, kelp (*S. latissima* and *A. esculenta*) and blue mussels (*Mytilus edulis*) are presently co-cultivated in Canada. Some mussel farmers use empty aquaculture horizontal longlines on their marine farms to cultivate kelp among their mussel lines. It has been observed that the location of some mussel farms is inappropriate for such co-cultivation, namely when the farm is located too close to an estuary: the large freshwater runoffs occurring during the spring are detrimental to the kelp (increase of water turbidity, growth reduction, blades covered with mud, blister disease on the blades) – but not to the mussels. This occurs even when the longlines are kept at 7 m depth. Where freshwater is not an issue, the co-cultivation of kelp and mussel is successful. Using the same longlines, boat and gears without any major modification is an advantage of this production system. Because kelp weight is almost neutral in water, the kelp longlines do not need as much buoy management as mussel lines. In addition, kelp is not impacted by molluscivorous marine birds. However, in contrast with mussel lines that can be kept at seven meter depth with no impact on their growth rate, the depth of the kelp lines must be adjusted twice during their culture cycle: they are lowered to 7 m depth in December in order to protect them from drifting ice in the winter, and pulled up again to 4 m in April to give the kelp access to more light. Spools with the kelp plantlets are produced by a private multi-species marine hatchery that operates a room for seaweed cultivation three months per year, from August to October.

II.6. Intensive farming

Scale is an important factor in the cultivation of seaweed, both as a commercial activity and as a provider of global ecosystem services. Asia offers appropriate conditions, large farms have existed for several decades for food production, with a yield of more than 20 million tons harvested in 2014 (Buschmann et al. 2017).

In Europe, current livestock operations are generally located near the shore and/or in partially confined water bodies (e.g. estuaries, fjords, ponds with fish farms nearby), so a lack of nutrients will generally not impact the expected crop volumes, nor are currents or wave action likely to constitute major obstacles. These water bodies are generally monitored to some extent due to current human activities. However, seaweed cultivation is still in its infancy, and the available sites are currently sufficient for the sale of higher value-added products such as food, pharmaceuticals and cosmetics. Future expansion to several million tons per year will require an increase in cultivation areas while respecting the spatial boundaries of existing activities and will required a multi-use of the coastline. One solution is offshore waters, in a fully exposed environment. However, few data are today available on the feasibility of seaweed aquaculture offshore. This issue has mainly been explored in the context of cultivation for bioenergy production in the Atlantic Ocean, which de facto requires very large seaweed farms. Initial concepts has been proposed, ranging from large-scale mechanised conventional anchored farms to floating units (see for example Roesijadi et al. 2008; SES 2013; OTEO 2014), but none of these concepts has been applied to date, due to the lack of economic feasibility of biofuel production from seaweeds or other uses requiring very large cultivation volumes.

II.7. Which techniques for the future?

The choice of cultivation technique depends on the life cycle and physical characteristics of the cultivated species. As a result, open-water, land-based farming and IMTA will need to co-exist in the future, with each technique offering its advantages and disadvantages (Table 3). The selected cultivation technique may also depend on local parameters and cultural practices.

Table 3: Advantages and issues raised by different existing seaweed-production techniques.

ADVANTAGES	TECHNIQUES	ISSUES	SOLUTIONS
Traditional Local economy Promotes female enterprise	**HARVESTING**	Potential over-exploitation of wild resources No legislation across EU Compliance Nagoya Protocol EU manual status not recognised	Define limitations/quota management/harvesting plan
High yield & year-round production Easy to harvest Controlled environment Consistent of high-quality biomass	**LAND-BASED CULTIVATION**	Needs of space on land High infrastructure costs High operational costs Less available knowledge on production protocols	Refurbish under-utilized structures in coastal areas (e.g. earthen-ponds, shellfish storage units). Renewable energy Promote biomass in added-value markets (e.g. food, cosmetics, health products)

Possibility to customize the chemical composition of biomass.			Foster research in production of target species
Low cost Can be 1D, 2D or 3D Open space	**AT-SEA CULTIVATION**	Low scale Farm location (nutrients, natural conditions, environment) Risk of escape Impact local genetic diversity Disease/multiple pests	Mechanisation & automation Env. condition monitoring Define geographical limits Balance inbreeding/ outbreeding programmes
Nutrient requirements Shared infrastructures & distribution channels Share investment and infrastructure (more viable on land-systems) Consumer acceptance	**IMTA**	Difficult to adapt traditional techniques of mono-aquaculture to combine the species. Best location for different species (depth, freshwater, estuary) Biosecurity Pests Lack of appropriate regulation	Best practices More research Modelling Collaboration with ongoing high-level trophic production sites such as salmon farm Simplify regulation; allow the co-exploitation of farming sites by different companies
Space Cost infrastructure investment for systems that can be deployed in open sea	**OFFSHORE**	Same as long line system International waters, resources beyond National jurisdictions Logistics	Best practices Modelling Collaboration with industrial fisheries and at sea transport companies are needed Collaboration with ongoing salmon farm developing activities in open sea

III - PRODUCTIVITY AND QUALITY – ENVIRONMENTAL FACTORS

Water quality is the most important factor to take into account when choosing the location for seaweed farming; heavy metals and microbiological quality (e.g. *E. coli*) should be closely monitored.

In some production systems, epiphytes and epizootics are problematic. For some applications such as polysaccharide extraction used for plant health or animal feed, epiphytes only contribute additional biomass and do not cause any major problem for the final product. However, when seaweed is grown for food or bioactivity, for which traceability and quality standards are strict, any visual contamination or loss of productivity by epiphytes is an issue.

Early kelp harvesting can be an effective way to avoid the most severe period of epiphytism (Peteiro & Freire 2013b). Epiphytes can also be controlled by good management practices such as handling inputs (mainly storage density) both on land and at sea or adding finer filtration systems and cleaning protocols on land-based productions.

Despite years of research and production development, diseases remain the main challenge inland agriculture and animal production face. Owing to the rapid intensification of seaweed farming, all indicators suggest that this burgeoning sector will not be exempt from this problem, as already illustrated by local seaweed industry outside Europe (Kim et al. 2014; Loureiro et al. 2015). Sooner rather than later, the disease issue will take centre-stage in worldwide algal cultivation preoccupation as for any other new domesticated species (Cottier-Cook et al. 2016). However, this is a common biological phenomena as seen in human health and medicine too.

Marine microbial diversity is nowadays one of the unknown components in world ecosystems, where roughly 90% of biodiversity is yet to be identified and characterised (De Vargas et al. 2015). A significant proportion of this diversity is associated with pathogenic lineages. Pathogens are increasingly recognised as an integral constituent of macro- and micro-algal communities. Some of them shape host-genetic pools and algal productivity, playing important roles in marine food webs (Neuhauser et al. 2011; Vardi et al. 2012; Avrani & Lindell 2015). Others raise serious problems for commercial seaweed farms in Asia. However, the pathogenic diversity of seaweed is currently a black box for the scientific community (Gachon et al. 2010; Loureiro et al. 2015). Recognition of these microbes is also problematic as most disease-causative pathogens are difficult to identify morphologically, and several of them are uncultivable by current microbiological methods (Loureiro et al. 2015). In this context, identification and characterisation of the diversity of infectious agents associated with seaweed in mariculture and wild populations are essential for the activity's success.

Also, treatment against pathogens is virtually unexplored. In contrast to consolidated agriculture and animal production, disease treatments are scarce for seaweed aquaculture. Mainstream treatments are either time-consuming, expensive, detrimental for the environment and/or useless to some extent. The only known treatments in Asia for *Olpidiopsis*/*Pythium* include *in-situ* acid washes of culture nets (Kim et al. 2014), calcium propionate (Jung & Kim 2017) and food-preservative salts with antifungal activity, associated with significant cost increases and very negative impacts on the environment. For activities carried out by local fishermen/small cooperatives, the protocols currently used to mitigate crop losses are rudimentary and/or too expensive. For *Gracilaria spp.* (Chile) and *Eucheumoids* (e.g. in Tanzania and Southeast Asia), such protocols include the complete removal of seedlings (Loureiro et al. 2015), which requires the launch of a new production cycle, or direct removal of the epiphyte load, which can account for up to the 60% of the crop's weight (Buschmann & Gomez 1993).

The possibility of controlling pathogens by prophylactic immunostimulation was recently tested for the first time in kelp (*Saccharina*) aquaculture in China and Germany (Wang et al., 2019). Loss of germlings was reduced during forced cultivation in greenhouses. Adults cultivated at-sea also exhibited less prevalence of endophytic algal pathogens when they were treated, but at the same time, they became more susceptible to epibiosis. Propagules of algae are known to settle preferentially on surfaces that are covered by certain bacteria which liberate chemical settlement cues into the water (Joint et al. 2007). The same or other bacteria associated with the biofilm then induce algal development (Wichard 2015). On the other hand, some other components of the seaweed microbiome provide protection from epibionts as they release deterrents (Nasrolahi et al. 2012). Targeted manipulation of the seaweed microbiome would require an in-depth understanding of its beneficial and detrimental components. However, such knowledge is not yet available. Moreover, the application options of immuno-stimulants or biocides in open-water culture are limited because of dilution effects and a highly probable impact on the environment.

IV -TIMESCALE FOR THE DEVELOPMENT OF COMMERCIAL SEAWEED CULTIVATION

Seaweed cultivation has not yet achieved widespread commercial viability in the Western world. In Europe, the development of cultivation activities will depend mainly on the demand from the food, nutraceutical and cosmetics markets, as these are the ones that pay the best price per ton of farmed seaweed. The annual growth rate of the seaweed food market in the EU has been estimated at around 10% per year (BIM report 2014).
The choice of the species to be farmed must follow market needs; as today, the production of some seaweed species is severely behind the demand (e.g. *Palmaria palmata*, *Porphyra* species, *Ulva* species, *Himanthalia elongata*, among others). So, there is a need to optimize production (increasing productivity with lower operational costs), adapt and/or simplify licensing and trading regulations. For that, R&D is mandatory in the several phases of seaweed production chain (breeding, farming and processing).

IV.1. Development of open-water cultivation

In Norway, 2 to 3 scenarios are being investigated for kelp cultivation at sea: small farms along the coastline, eventually connected to salmon farms (IMTA) either land-based or at-sea, and large facilities under open-sea “offshore” conditions.
For cultivation activities in coastal – and even more so, in offshore - waters, it is difficult to predict a timescale for development, due to the still-uncertain market prices achievable by different components, and also due to the current infancy stage of the biorefinery concept and the whole value chain need to be developed to finalise the production of high value products.

With food being the primary target for brown seaweed cultivated at sea, growth to several thousand, possibly even tens of thousands of tons per year appears realistic at a timescale of 3-5 and 10-20 years, respectively. In Europe, with available cultivation techniques and assuming in-house seedling production, production becomes economically interesting from upwards of a few hundred tons per year at current market price levels. The major seaweed cultivators in Northern Europe produce in the range of several tens to a hundred tons, which indicates that coastal/offshore seaweed farming for human food is on the tipping point to commercial viability. Once this has been achieved, economies of scale and investments into more competitive farming techniques will drive down costs and allow for much larger volumes for lower-value markets.

At the same time, biorefinery will advance, and high-value components can be extracted before the bulk is used for lower-value applications like fish feed. Such a development will entail an increase to tens or hundreds of thousands of tons per year in Europe, implying single farm units of several thousands of tons, likely to be installed in more exposed, further offshore waters (due to factors including a lack of primary sites and potential conflicts of use). For land-based operations, this will only be possible in scenarios where existing and under-utilised infra-structures are refurbished.

According to an optimistic estimate, such a scenario could be reached in approximately ten years while a more conservative approach suggests that it will not occur before 2030.

The costs for harvesting, pre-processing and processing the raw biomass will affect the choice of scenario made for production systems, both at sea and on land.

Mechanisation and automation, reduction in transportation times and volumes are key aspects.

IV.2. Development of land-based cultivation

Some seaweed species can only be successfully grown in land-based systems (either in tanks or raceways). Success in this context means high yields, the potential to apply stress protocols for target compounds, and year-round production. Land-based production is easier to couple with on-site processing. However, these systems require access to land space and have high energy usage. Solutions consist of:

i) Refurbishing existing and under-utilised infrastructures: earthen ponds, shellfish storage tanks.
ii) Using renewable energy to supply production/processing systems.

Current demand from the European food market alone for sea lettuce (*Ulva* spp.), Dulse (*Palmaria* spp.) and Atlantic nori (*Porphyra umbilicalis* or *P. dioica*) is estimated at several thousand tons (DW) for use as sea vegetables or ingredients. This increasing demand focusing on local products has opened a highway for the development of land-based cultivation of these species.

Today there is not enough seaweed biomass (wild and farmed) to satisfy demand, although estimations of current production remain approximate (a value of 60-80 tons (FW) in 2017 should be close to the reality for *Palmaria*).

For *Ulva*, farmed production will foreseeably increase rapidly in the next five years, given the ongoing projects involving this seaweed in Europe; ALGAplus, a Portuguese SME, expects to move up from 23 tons cultivated in 2017, to 40 tons in 2018 and 200 tons (FW) by 2019.

The development of Atlantic nori and dulse production will be slower and harder to predict as success in growing them was reached only recently. Future evolutions will greatly depend on investments made to secure efficient production methods for these species.

V - PRODUCT PROCESSING AND MARKET SUPPLY

After collection, and before further processing, seaweeds should be washed using either seawater or freshwater, depending on the end-users. Different alternatives for final products include drying (preferably at low temperatures and up to a final moisture content of 10-12%), freezing (preferably Individual Quick Freezing) and mixing with salt/or brine.

V.1. Drying

Drying is the most common method for stabilising wet macroalgal biomass. Drying reduces the water activity of biomaterials, thus increasing the shelf-life of products, by deterring microbial growth and other degradations as a result of chemical and enzymatic reactions. In addition, the material weight and volume are substantially reduced, hence minimising packaging, storage and transportation costs. Seaweed is typically preserved using hot-air convection drying. However, the chemical content (Gupta & Abu-Ghannam 2011; Tello-Ireland et al. 2011) and physicochemical properties of the material may be affected (Sappati et al. 2017; Stévant et al. 2018), bringing consequences on the product's nutritional value and extraction yields for valuable compounds. Also, air-drying is energy-intensive, which makes it difficult to implement close to the harvesting sites - locations favoured for rapid processing of large biomass volumes. As a result, this type of drying altogether lowers the environmental and economical sustainability of the processing chain. Alternative drying technologies such as infrared, microwave and superheated steam drying are gaining priority in the food-processing industry in the bid to improve energy efficiency as well as product quality (Rahman & Perera 2007). However, little data is currently available regarding the benefits of these technologies when applied to dry seaweed biomass. Also, drying and processing facilities can occasionally be contaminated when they are used for other biomaterials (as in Norway) or when operator or equipment hygiene is lacking. Therefore, algae should follow the same bacterial-contamination analyses as other seafood products.

Drying may be associated with high operating costs, and, therefore, may not be adapted to the provision of certain products with low commercial value.

V.2. Anaerobic fermentation

Anaerobic fermentation techniques (also referred to as silage processes) - adapted from terrestrial agriculture using microbial strains - offer an attractive alternative to drying seaweed biomass (Herrmann et al. 2015). Generally, fermented food and feed products are more readily digestible compared to their unfermented counterparts, and the potential of fermentation processes for increasing the digestibility of seaweeds has been demonstrated in earlier studies (Fleurence 2004; Marion et al. 2003). In addition, the prebiotic activity of seaweed polysaccharides, especially oligosaccharides - reported in previous studies (see references in O'Sullivan et al. 2010) - could potentially be boosted by enzymatic processes. In order to facilitate the consumption of seaweed nutrients, natural lactic bacteria present on the seaweed could be added for the fermentation process. Furthermore, enzymatic treatments can also improve the extraction yield of bioactive compounds from seaweeds. For instance, xylanase enzymatic hydrolysis of *P. palmata* can enhance the recovery of R-phycoerythrin (Dumay et al. 2013; Dumay et al. 2015). Cellulase, β glucanase and xylanase enzymatic treatments increase the *in-vitro* protein digestibility of *P. palmata* (Fleurence & Guéant, 1999; Fleurence et al. 2001; Patent application (Method for extracting and improving digestibility of *P. palmata* proteins EP 1301088 B1; Fleurence et al. 2002). Similar results can be expected from the use of enzymes on brown seaweeds, with the beneficial impact of pigment extraction or protein digestibility.

All fermentation-related processes investigated need to respect European regulations on both fermentation (Regulation (EC) No 852/2004 on the hygiene of foodstuffs) and enzyme use (Regulation (EC) No 1332/2008 on food enzymes).

Enzymatic treatments can also improve the extraction yield of bioactive compounds from seaweed.

V.3. Freezing

Freezing is one of the most widely used methods for long-term food storage. By changing the physical state of liquid water in food into ice, the growth of microorganisms is stopped, and the rate of biochemical reactions governing food deterioration is limited. Loss of quality in frozen foods primarily depends on storage temperature and duration, as well as thawing procedures (Rahman & Velez-Ruiz 2007). Many studies have focused on improving the quality of biomaterials (e.g. fruits, meat, fish) but little attention has been paid to optimisation of the quality of frozen seaweeds (Choi et al. 2012). While optimal freezing protocols for foods aimed at maintaining tissue integrity, and the biomaterial's textural and sensory attributes, radical alterations such as extensive cell rupture may facilitate the recovery of intracellular compounds through fractionation processes.

VI - AQUACULTURE MANAGEMENT

In 2014, the Northeastern Regional Aquaculture Center in the USA published a manual to help farmers identify and manage aquaculture production hazards, with a chapter on seaweed (Getchis 2014). The document covers environmental conditions, biofouling organisms, predators, diseases and parasites, invasive species, and operational procedures related to seaweed aquaculture (Getchis 2014).

In Europe, the Aquaculture Stewardship Council (ASC) and the Marine Stewardship Council (MSC) Seaweed Standard for environmentally-sustainable and socially-responsible seaweed harvest and aquaculture was released in November 2017. It applies globally to all locations and scales of seaweed operations, including harvesting of both wild population and cultivated seaweeds. The Seaweed Standard has been effective since 1 March 2018 (ASC Aqua 2018). The five guiding principles are: Sustainable wild populations, Environmental impacts, Effective management, Social responsibility, Community relations and Interaction.

Photo credit: Jez Tims from Unsplash

CHAPTER IV –

CHALLENGES IN THE SEAWEED-CULTIVATION PROCESS

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Photo credit: Ray Bilcliff from P*EXELS*

The potentially severe, unpredictable, and often irreversible environmental impacts of seaweed aquaculture raise challenges that need to be answered. Among them are the introduction of alien species and the risk of transmission of parasites and pathogens to wild populations, the impact of escapees, and the management of waste (Table 4). Below, the potential consequences of taking such risks are described, and alternative solutions are proposed. These must be developed and adapted on a case-by-case basis.

I - SOURCING

In the history of agriculture, the improvement of seaweed aquaculture has followed the following steps: *i)* wild harvested strains; *ii)* the development of efficient technical itineraries, and *iii)* breeding/selection of progeny (Liu et al. 2016).

A current key issue for sustainable seaweed aquaculture is the origin of the cultivated seaweed. In practice, it can be harvested from either wild populations, or from a pool of artificial strains that have already gone through the selection process. Seaweed multiplication then requires individuals having reached a reproductive stage, either through the formation and propagation of vegetative organs (e.g. propagules) or through the dissemination of germ cells (gametes, spores).

In this section, we explore the challenges associated with this origin ("sourcing"), which implies the prior characterisation of wild resources. We also address how to identify good ecological practices to establish sustainable diversity management in wild stocks. Finally, we summarise the main advantages and limits of each sourcing technique (see Table 3).

I.1.Origin of cultivated strains

I.1.1 NON-INDIGENOUS SPECIES

1.1.1 Risks of invasive species

The exposure of native species to invasive species may result in cascading consequences on the ecosystem because invasive species usually support a different community. Therefore, the occurrence of negative effects, but not their weight of impact, can be anticipated when introducing invasive species.

Invasiveness

Invasive species can occupy environments free from similar native species and alter environmental conditions when they exploit resources that are unused by the native populations. In addition to biological and environmental risks, invasive species can also present economic risks. They can have an impact on artificial structures, for example by occupying submerged surfaces to the extent that swimming and boat traffic in marinas are hindered, or by obstructing water-intake structures, used for example to take in cool water.

Although a minority of introduced species have today established large populations and extend along large areas of the European coastline, there is an inherent risk of adverse impacts on native ecosystems. In general, environments under strong human influence appear to present the highest risks related with marine species invasion.

Aquaculture species can become invasive if they cannot be contained in the facilities and can propagate and multiply sexually or asexually in the natural environment. A typical illustration is the Asian edible species *U. pinnatifida*, which was accidentally introduced to France through oyster importation, and then in 1983, deliberately transplanted to Brittany for aquaculture trials. Since then, there has no longer been any flow between farms and natural populations (Guzinski et al. 2018) and maritime transport seems to be primarily responsible for its dispersion and mainly happened in harbours.

Well-studied examples of introduced species with a demonstrated negative impact on coastal ecosystems (invasive species) in Europe include *Sargassum muticum, Caulerpa cylindracea, Caulerpa taxifolia* and *Womersleyella setacea*. The CIESM Atlas presents a detailed map and description of new invasive macrophyte species observed in the Mediterranean (Verlaque et al. 2015).

Impact on human health

Domestication and the use of unintentionally introduced seaweeds for nutrition purposes may not only pose a risk to the environment, but also the consumer. Newly introduced seaweed populations are usually descended from single individuals that have successfully resisted novel species of herbivores and other novel biological enemies in the newly established environment. As a consequence, they may have been selected for increased deterrence of such enemies and increased toxicity to humans *(also see Chapter VI on Challenges in Food safety)*. It was demonstrated for *Gracilaria vermiculophylla*, an invasive species from East Asia, that developed an increased capacity for production of prostaglandin and related compounds when establishing in its new territory. These are toxic to mollusc-feeding enemies, but also human consumers (Hammann et al. 2016).

"The multiple facets of global change, such as aquaculture practices, habitat modification and increased traffic, act in synergy on a global scale, facilitating the introduction of pandemics" (Voisin et al. 2005). This observation suggests that:

i) It is difficult to estimate the invasive potential of a non-native species, as it depends on many environmental and biological factors.
ii) The invasion process must be studied specifically for each non-native species.
iii) Only a multidisciplinary approach will allow us to fully understand the invasion process.

Therefore, it is necessary to avoid intentional introduction of non-European species at all times.

1.1.2 Risk of proliferation of non-indigenous pathogens and pests

In the marine ecosystem, seaweed provides food and shelter for various microorganisms (Goecke et al. 2010; Goecke et al. 2013) such as fungi, bacteria and viruses (Gachon et al. 2010, Wichard 2015) and various epibionts (Wahl 1989) such as vertebrates, small to large browsers and other animals (Anitchanant 2013). As for all seaweeds, non-indigenous species are associated with many organisms which are unavoidable in the cultivated marine environment (Yamamoto et al. 2013), including pests (Ingle et al. 2018). Through the amendment of the definition of “harmful organisms" (FAO 2014) developed by the International Plant Protection Convention (IPPC), the term in aquaculture now refers to "any species, strain or biotype of plant, animal or pathogenic agent, potentially harmful or harmful directly or indirectly to cultivated seaweeds or their products" (Ingle et al. 2018). In Figure 17, potential pests are mapped.

Therefore, although many non-native crop species are not invasive, they can serve as vectors for the introduction of pathogens or pests. Toxic invaders can affect human health either directly or indirectly, e.g. by promoting the accumulation of toxic compounds or agents (pests) in other organisms that are intended for human consumption (e.g. abalone, sea urchins, herbivorous fish, etc.).

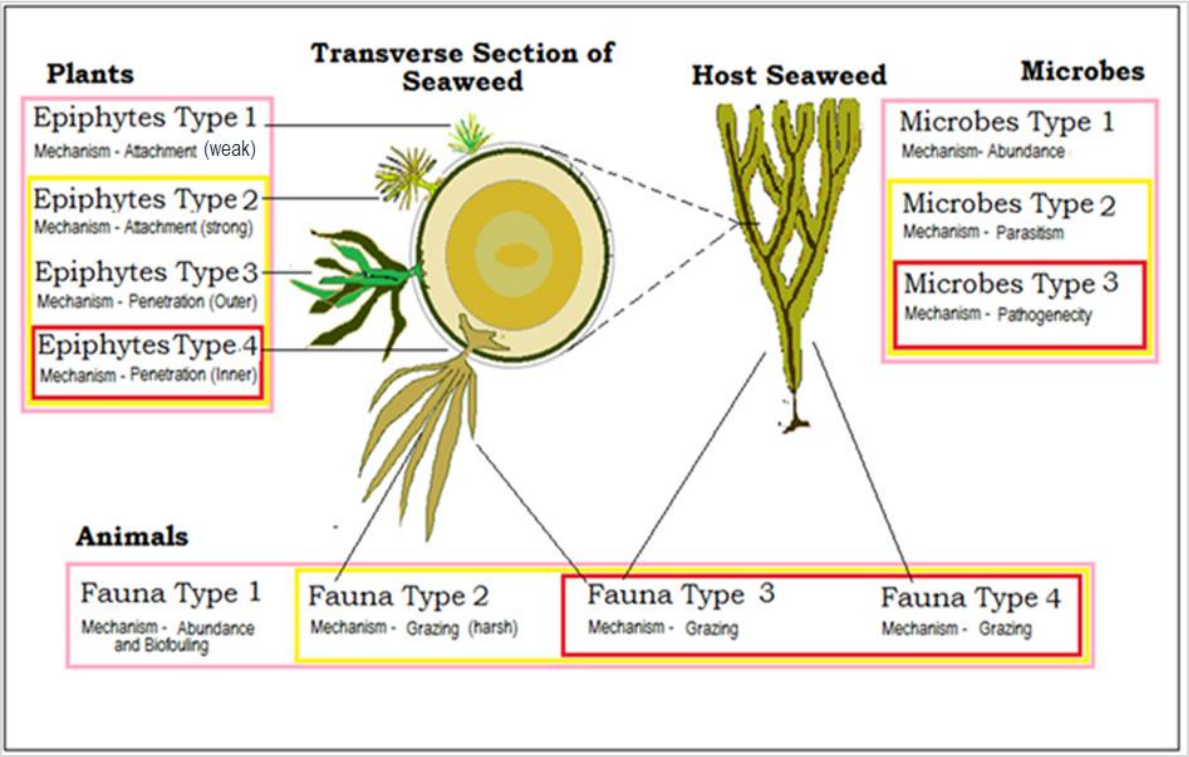


Fig. 17: Potential risks of pests & pathogens (Courtesy K. Ingle, from Ingle et al. 2018).

I.1.2 INDIGENOUS SPECIES AND THE RISK OF IMPACT ON LOCAL DIVERSITY

1.2.1. Local versus distant populations: Defining the geographical limits of "local strains"

It is difficult to define what is local and what is not, when an offshore farm is considered as the geographical reference from which the natural resources available for cultivated species are explored. How far from this farm can organisms still be considered as belonging to the "local population"? This question is crucial because the answer will determine the geographical boundaries beyond which populations may not be well adapted to farming conditions. Indeed, growing individuals from a remote population could lead to lower productivity and a loss of quality. In addition, non-local individuals transferred to the farm may have a significant impact on the wild populations there (see below for further discussion on this point).

The compatibility between a local and a distant population must be tested before a species is cultivated.

In this way, the mere presence of a species found growing near a farm is not enough to guarantee the crop's success. A more profound knowledge of populations and their relationships (i.e. gene flow) is needed to identify better the optimal supply areas from which farmers should harvest fertile individuals and then produce "local strains" (Luttikhuizen et al. 2018).

1.2.2. Inbreeding/outbreeding effects and impact on genetic diversity

Breeding programmes aim to combine or purify the characteristics of different strains to improve the traits of a strain. In Chapter III, Section I "Sourcing", we described the two ways individuals can be crossed (inbreeding or hatching) in anticipation of different results (integration of a trait of interest into another genetic context or selection of a pure lineage).

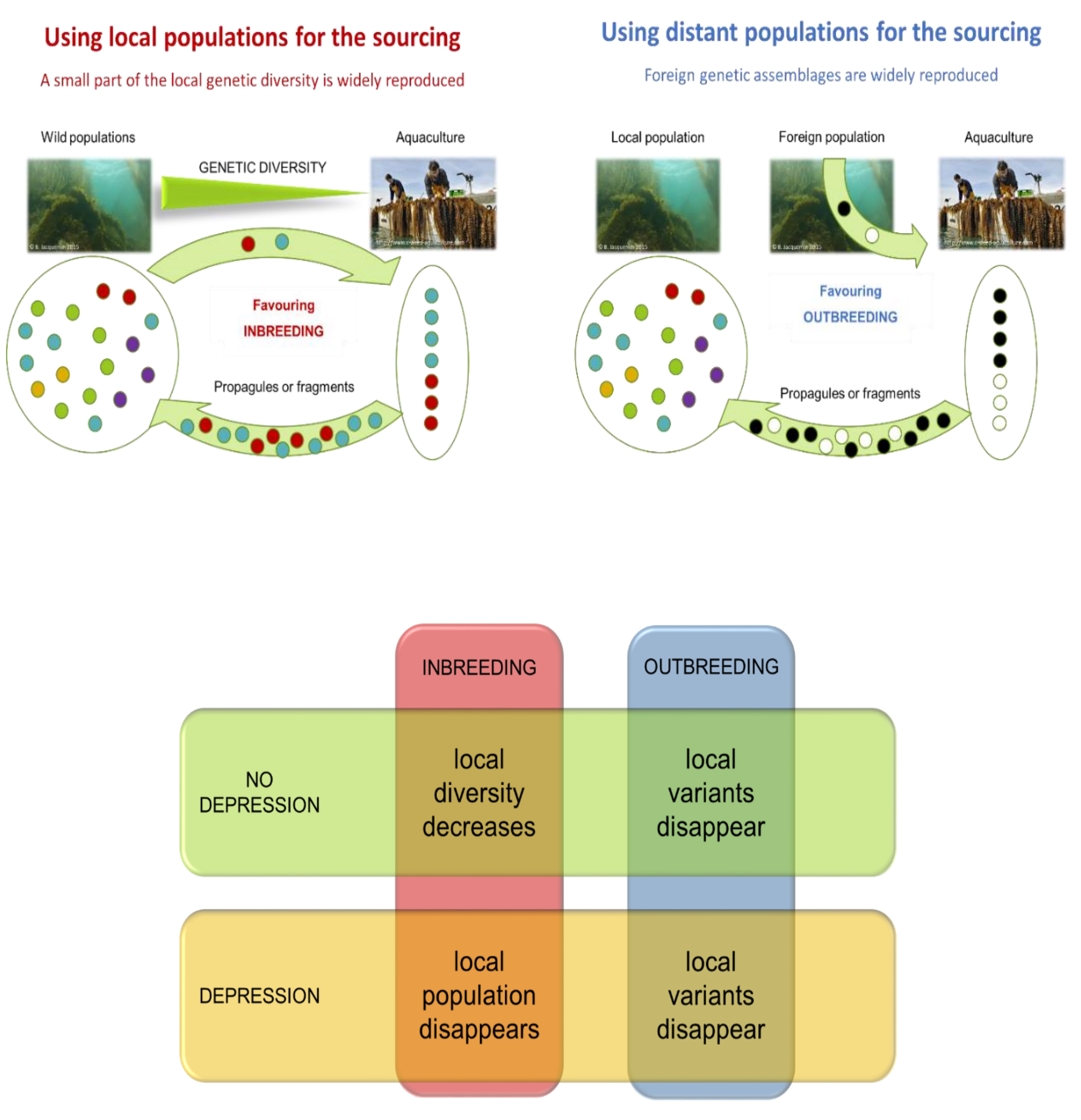
However, it is not easy to manage gene assemblies via controlled crossbreeding between strains, and a given type of crossbreeding can produce very different effects from one species to another. For example, for species where self-fertilisation is dominant, crosses between unrelated populations can be difficult or impossible. On the other hand, for strictly allogamous species or species displaying self-incompatibility responses, breeding programmes based on uniparental lineages would be limited. Upscaling of macroalgae cultivation further demands increasing the genetic diversity of the breeding population to avoid inbreeding depression. Moreover, as presented in Chapter III section I, the phenotypic response to different kind of crosses (inbreeding or out-breeding) is unpredictable as this refers to specific genetic and evolutionary mechanisms within each species. So, there is a real need of a better understanding of the reproduction strategies for each species of interest.

Once a new strain is generated through breeding, its confinement becomes the first issue. Studies have shown that crosses between cultivated seaweed and native stocks can result in the decrease of local genetic diversity, further impacting the dynamics and local adaptation of the populations and then ecosystem resilience (Jacquemin 2017va, b; Valero et al. 2017; Hutchings & Fraser 2008). Therefore, the capacity to prevent the dispersion of individuals or propagules is an important challenge for sustainable aquaculture as a case by case estimation of the genetic compatibility patterns is needed for each cultivated species.

> ***"As marine environments are less controllable and are more variable than land-based systems, breeding should aim at improved strains adapted to the local environment as well as preventing the introgression of unsuitable genes in natural populations."*** Potin et al. 2017.

So, for each cultivated species, cross experiments should be run to test the compatibility between local and distant strains, and thus evaluate inbreeding and outbreeding effects (Figure 18; also refer to the definition of "local strain" in the Glossary). This is a long-term assessment which should involve all the stakeholders.

As a consequence, only experiments conducted under controlled conditions or on-site studies where cultivation already happened can help to promote a better understanding of the genetic combinations that would be optimal for cultivation and predict the consequences of escaped individuals from the farm to wild populations.



	INBREEDING	OUTBREEDING
NO DEPRESSION	local diversity decreases	local variants disappear
DEPRESSION	local population disappears	local variants disappear

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Fig. 18: Potential impact on genetic diversity when using either local or distant populations for the sourcing of the cultivated population (© Bertrand Jacquemin, CEVA).

Table 4: Summary of advantages and limits of the different sourcing techniques. The species can come from either the natural habitat (wild) or a seaweed collection. If the populations are wild, they can be non-native species with the risk of invasiveness and epiphyte introduction, or they can be native species coming from a local or a distant population. In the latter case, some limits and challenges exist.

Species origin			**Advantages**	**Limits & Challenges**
Wild	**Non-native species**		Access to new products Supply a larger market	Might be locally unadapted Risk of environmental impact Risks of invasive species, pests /diseases, epiphytes/epibionts
	Native species	**Local population**	Easy access Have adapted genetic background	Local traits matching the market Identification of the traits expected for the market Large range of diversity enabling the deployment of selection programmes
		Distant population	Access to new traits	Might be locally unadapted Risk of environmental impact Provision cost Suitability for breeding programmes Varietal creation Potential environmental impact on the trait of interest
Banks & seaweeds collections			Traceability of the traits Long-term storage Free sourcing from wild resources	They are not yet developed Requires improvement of preservation techniques Need to implement technical centres & certification centres

1.2.3 - Breeding of species listed on the Red List for conservation/ restoration purposes

Seaweed aquaculture can be expected to provide conservation and/or restoration programmes where a species has begun to disappear. On the one hand, if local populations decrease due to a permanent change in environmental conditions (global warming, habitat destruction, etc.), these conditions will not be favorable to crops either. Trying to grow a species where conditions are not favorable is nonsensical. On the other hand, in the case of temporary environmental disturbance, seaweed aquaculture can regenerate populations. The main challenge, in this case, will not only be to produce a large number of individuals, but also to generate appropriate genetic diversity.
For any “Red-listed” species, the causes of their local extinction must be identified before contemplating any conservation/restoration programme.

I.2. Attaining the “best cultivar”: Selection of traits of interest & improvement of strains

The best cultivar characteristics should match the market’s demand criteria. Its selection can necessitate a combination of genotypes (i.e. gene assemblies) that is not found in the wild *(see Chapter III on Seaweeds production and cultivation, section I.3)*, through forced sexual reproduction. The challenge is then to identify the strains that 1/ hold the ToI and 2/ will be able to cross each other (no reproduction incompatibility).

Usually cultivars should combine robust characteristics (disease resistance, epiphyte) and rapid growth. However, many seaweeds have a high phenotypic plasticity (i.e. varying traits in different environments). Understanding how certain relevant traits have been selected through evolution and identifying their genetic determinism (i.e. how traits are inherited from parents by progenies) require a great deal of attention. Strain selection is, therefore, an intensive, time-consuming and expensive process. However, there is no way to bypass it.

Quantitative genetics is presently used for seaweed selection but requires even more research. In cases where clonal cultivars have been produced and used for some species, the impact on genetic diversity has been significant. Some relevant examples are the clonal production of new cultivars for *Gracilaria chilensis* and *K. alvarezii*. Both species are mainly cultivated by the vegetative reproduction of fragmented individuals, and selected traits have focused on fast growth and high biomass production (Alveal et al. 1997; Hayashi et al. 2010; Hurtado et al. 2015). For these two seaweeds, genetic depletion and loss of genetic diversity have arisen due to genetic bottlenecks, i.e. a substantial proportion of a species’ population disappears or is prevented from reproducing (Guillemin et al. 2008; Halling et al. 2013; Guillemin et al. 2014).

The main challenge will not only be to produce a great number of individuals, but also to generate adapted genetic diversity.

Since the shape and beneficial components in a same species may vary according to seasons and geographical regions, attention should be paid to the temporal and geographical distribution of the ToI (both the range of its variation and how this can be controlled or predicted).

Many compromises are necessary to find the right strain of each species under the right conditions (Figure 19). For example, it does not follow that a strain selected for asexual reproduction (faster and cheaper) will have better yields.

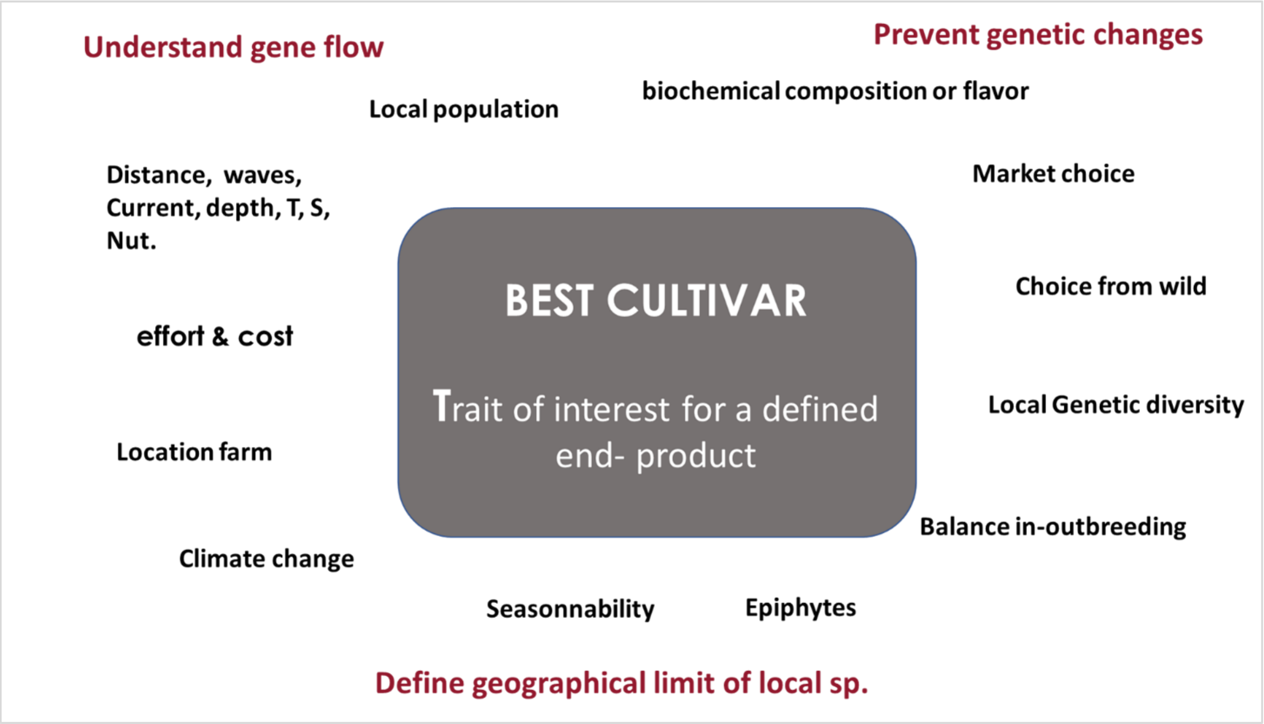

Fig. 19: Many factors influence farming conditions for the best cultivar
(© Michèle Barbier, Institute for Science & Ethics).

I.3. Strain collections

For the maintenance and exploitation of seaweed resources, genetic-improvement programmes are recommended through the collection, isolation and continued maintenance of wild strains in uni-seaweed culture-stock collections (Charrier et al. 2015) (Friedl & Lorenz 2012). Indeed, genetic germplasm banks (i.e. strain collection and management) provide an opportunity for genetic selection, clone creation, strain preservation, and the generation of large quantities of gametophytes by vegetative growth that can produce seedlings at any time of the year (e.g. in *S. latissima* and other kelp species; Peteiro & Freire 2014; Peteiro et al. 2016 a, b).

The establishment of such strain collections would allow each farmer to keep a long-term backup copy of his/her "best cultivars" and to have a wide variety of sources for breeding and selection programmes. This would provide a reliable source of cultivars well adapted to the local environment in the event of a temporal or permanent decrease in the wild stock.

Strain collections in germplasm banks present important advantages such as:

- possibility of genetic selection
- production of clones
- preservation of strains
- generation of large quantities of gametophytes through vegetative growth
- production of seedlings at any time of the year.

II - CULTIVATION TECHNIQUES

Kelp processing is a challenge as large amounts of biomass need to be dealt with in a short time - a requirement that strongly calls for the development of automation, especially for offshore cultivation. This development would also contribute to reducing operational costs due to the repetitiveness of the labour involved.

In addition, some specific traits of seaweeds, or else species that cannot withstand waves/currents in systems at sea, can have high commercial value and justify investment in more expensive production systems like land-based tanks. However, not much progress has been made in this field since the work of the Ryther team in the 70s, so innovation and investment in the design and development of newer systems are necessary. The main strategy, besides strain selection, for controlling the reproduction steps and optimising biomass yields, consists in adjusting the stocking densities (effect on light and nutrient availability) and water-renewal rates (effect on temperature and nutrient availability). However, each protocol is species- and season-specific, and will require adjustment for each farm location.

Sub-sections below raise issues related to offshore and on-land cultivation systems.

II.1. Offshore farming challenges

Offshore seaweed cultivation is a new specific area of RTD, given the existing lack of antecedents for farm structures, seeding/deployment, harvesting and transporting of large seaweed volumes in this environment. At first sight, one might detect some resemblance to fish trawling and some other techniques in aquaculture (fish handling and well boats; mussel farming), but none of these techniques has proven viable options for seaweed farming so far (OTEO 2014). The physical characteristics (size, weight, stiffness) and degrees of freedom of movements of several connected floating bodies (farm structure, carrier - without/with growth - and lead ropes, vessel) are unusual combinations that, in conjunction with environmental forces (current, waves, wind), raise a complex challenge, nearly impossible to simulate on a small scale or numerically.

A factor likely to influence the farming techniques for exposed locations is the rapid development of marine robotics; autonomous vehicles may play an important role in future inspection activities, as well as potentially harvesting, (re-)seeding and transport operations. By the time very large offshore farms become a reality, autonomous marine operations may have evolved to a point that a significant part of the solution towards the above-mentioned challenges.

The timescale development of future offshore seaweed farming will not only depend on the resolution of the above technical challenges, but also on the extent to which the ecosystem services that seaweed might provide will be proven and factored into economic evaluations (including meaningful incentives or public investments). The development would thus be fostered by the promotion of large seaweed-cultivation farms as contributors to ecosystem conservation, with a similar role to terrestrial reforestation.

II.2. Disease risks

Disease susceptibility is a problem in seaweed farms, encompassing up to 50% of farm running costs (Kim et al. 2014). Historically, to tackle this problem, seaweed farming has pursued selection of strains by choosing parents with desirable features and backcrossing them for several generations (Zhang et al. 2007). However, a consequence of this inbreeding is a significant reduction of genetic diversity, and, therefore, a potential loss of stress-related genes, for example, related to disease resistance. If these individuals are released into the environment (as in coastal aquaculture), genetic pollution can follow

from the intercrossing of wild and cultured parents (Voisin et al. 2005; Liu et al. 2012). In a broader sense, it is indispensable to develop strains with desirable traits (e.g. disease resistance), which are part of the local biodiversity and ideally cannot succeed in colonising the wild populations. There is solid evidence that not all algal individuals from a single species respond equally to diseases, and some can remarkably stand up against pathogens (Gachon et al. 2009; Allewaert et al. 2018). Accordingly, the use of tools to genetically map populations for features of interests, as developed for plants (GWAS), is a promising option for seaweeds (Barabaschi et al. 2016).
Disease risk during the seaweed-production cycle can be roughly divided into three stages:

II.2.1. RISKS IN THE LABORATORY STAGE

Most seaweeds are very susceptible to disease and pests in their early development stages (Guan et al. 2013; Gachon et al. 2017). However, this risk can often be significantly reduced by good practices such as prophylaxis and sterilisation of reproductive material, consisting mainly in the selection of healthy parents and subsequent disinfection/cleaning of reproductive tissue before sporulation/propagation (Westermeier et al. 2006). When these measures fail, the seaweeds are prone to problems such as grazers (e.g. ciliates) that decrease the productivity of the culture. Bacterial and diatom blooms may also overgrow micro stages of kelp and red seaweeds, and occasionally deplete available nutrients quickly. In rare cases, some pathogens can manage to survive and develop in unialgal cultures, especially when the cultivated species has a complex life cycle (McKeown et al. 2017). After an outbreak or biological contamination at this stage, the most reasonable action is to discard all the material. However, where cultures are very valuable, chemicals may be applied: they range from antibiotics against bacteria (Müller et al. 2008), germanium dioxide against diatoms (Shea & Chopin 2007) and iodine against ciliates (Yarish et al. 2017). Alternatively, some farmers prefer to increase the rate of water/culture medium change, which decreases the amount of undesirable escorting microorganisms (private memorandum: Jacquemin & Abreu 2018).

Many of these infection risks can be reduced by axenic or unialgal germplasms, which not only act as backups of natural population seed stocks (Westermeier et al. 2006), but also offer a good starting point for aquaculture with a predictable good sanitary state. Axenic cultures also offer important advantages for fundamental and applied research, especially where the total absence of foreign DNA and metabolites is essential (Müller et al. 2008, Wichard 2015).

II.2.2. RISKS IN GREENHOUSE CULTIVATION

Some seaweeds/cultivation systems require an intermediate production stage in order to obtain bigger plants before outplanting. During this stage, water seaweeds are cultivated in ponds/tanks, whose water is (normally) filtrated for big particles (ca. 45 µm) and adjusted to constant temperature and movement. The light and photoperiod are typically natural, and hence season-dependent. While disease outbreaks have yet to be recorded at this stage for seaweeds, it is clear that for the microalgae *Haematococccus pluvialis*, cysts of its blastocladialean fungal parasite *Paraphysoderma sedebokerense* may be very resistant to disinfection techniques in ponds (Allewaert et al. 2018). Therefore, there is no absolute certainty that such disinfected ponds may not be a hotspot of potential infection either.

II.2.3. RISKS IN MARICULTURE FACILITIES

Due to the broad dynamics of the open sea, this phase is the one that offers the least controlled conditions, and hence the most challenging, in seaweed aquaculture. Out-planted individuals move from relatively stable culture conditions to a highly fluctuating and stressful environment. Biological factors such as competition, herbivory or diseases/pathogens (which were limited in previous stages) may dramatically rise as important bottlenecks during this stage.

Disease outbreaks have been observed in both cultivated kelp and natural stocks in Europe and the rest of the world. Unfortunately, in most cases, their epidemiological and aetiological aspects are at best poorly understood. Massive mortalities in wild populations of the kelp *Ecklonia radiata* have been linked to the presence of novel ssDNA viruses in diseased (bleached) individuals (Beattie et al. 2018). This suggests a potential control of viruses over kelp demography, in the same way as viruses control some phytoplankton blooms (Frada et al. 2008). Bacterial infections have been strongly correlated with the ice-ice rotting syndrome of *Kappaphycus* and *Eucheuma*, which supply the worldwide hydrocolloid industry (Largo et al. 1995). Over the last 15 years, this syndrome has become the most devastating disease for cultivated eucheumoids, causing long-lasting regional industry collapses (e.g. in Tanzania, see Msuya & Porter 2014) and recurrent losses elsewhere. Bacteria have also been reported in kelp and nori aquaculture (Sawabe et al. 1998; Kim et al. 2014). In several cases, bacterial diseases seem to be related to a microbial dysbiosis (e.g. change of the microbiome structure) rather than a particular pathogenic entity or entities. This microbial dysbiosis has also been observed in heat-stressed red alga Delisea pulchra, causing the decimation of entire populations in southern Australia (Kumar et al. 2016). The proliferation of pathogenic bacteria is commonly linked with high host density in other aquaculture species (Krkosek 2010), and therefore more outbreaks are expected as seaweed aquaculture intensifies. Worryingly, pathogens, like any other organism, are affected by rising temperatures and it is hence expectable that their frequency and virulence will vary with global warming.

II.2.4 FUNGI AND FUNGAL-LIKE PROTISTS

Other pathogens include fungi and fungal-like protists. Water moulds (oomycetes) are serious threats in plant and animal systems. Likewise, *Olpidiopsis spp.* and *Pythium porphyrae* are devastating pathogens in Asia's nori production. Records *of Olpidiopsis* have increased over the last years to more than 10 species that can infect Bangiophycidae and Florideophycidae, and since it is broadly distributed in Europe, it may be an important threat for regional red-algal mariculture (Badis et al. 2017). Additional pathogenic oomycetes include brown-algal parasites *Eurychasma dicksonii* and *Anisolpidium* spp., which can infect both gametophytes and sporophytes of economically important kelps (Müller et al. 1999; Gachon et al. 2017). Due to their cosmopolitan distribution and wide host range, they potentially can reach farmed European kelps using ephemeral and perennial brown algae as intermediate hosts.

II.2.5 FILAMENTOUS BROWN ALGAE

Endophytic filamentous brown algae are commonly found in kelp populations. They asymptomatically coexist with their host at levels that only can be recognised by very sensitive tests (such as qPCR) (Bernard et al. 2018); however, depending on their propagation, they may negatively affect kelp growth patterns and rates. The brown-algal endophytes of genera *Laminariocolax, Laminarionema* and *Microspongium* are highly prevalent in European wild-kelp populations (Bernard et al. 2019; Murúa et al. 2018). They invade seaweed stipes and fronds, and in some instances can severely perturb morphogenesis and promote detachment. Much easier to recognise (but also more common in farms) are epiphytes, small individuals (algae but also other sessile organisms) that use cultivated kelps as habitats/substrata. At low prevalence, they are mostly innocuous for their hosts. However, some of them can develop long rhizoids that penetrate deeply in the inner tissues (i.e. medullae), causing detriment to the host (Leonardi et al. 2006). They can also overgrow the host and compete for nutrients, gases, and light (reviewed in Hurd et al. 2014). In the worst scenario, they significantly increase drag forces (enhancing detachment) and add a significant amount of weight that prevents their host from reaching superficial (e.g. more illuminated) waters.

III - PROCESSING AND MARKET SUPPLY

The final product will determine the qualities that a cultivar should display (e.g. potential for bioenergy requires high sugar content; application in animal-feed ingredients requires high protein content).

Industrial utilisation of macroalgae is rapidly developing in Europe, where the final products have several applications such as food and health, feed, manure, biofuels and chemicals. One of the main challenges for industrial players is to preserve biomass since seaweeds are characterised by rapid microbial decomposition once harvested, sometimes far from where they are processed (Enríquez et al. 1993). Substantial volumes are typically harvested within a limited timeframe (approximately 4-6 weeks for *A. esculenta* and *S. latissima*) in large-scale cultivation, setting standards for efficient processing strategies (Stévant et al. 2017c). Preservation methods that: *(i)* minimise losses of valuable compounds, *(ii)* ensure product safety, and *(iii)* limit energy use and associated costs, are keys to increasing the industry's profitability.

To further develop the industry, it is also important to investigate relevant pre-treatment steps coupled with efficient production systems to stabilise seaweed biomass after harvest and achieve high-quality products which may undergo further conversion steps. The sustainability of preservation processes should also be assessed from a techno-economic perspective. Efficient stabilisation alternatives as well as optimal procedures to prepare the biomass for chain extraction of high-value components, will ensure access to seaweed biomass all year round and sustain the growing demand for bioactive substances. This will create value in the coastal industry and support the sustainable development of the European bioeconomy based on the cultivation and processing of macroalgal biomass.

Despite a large body of literature reporting on the bioactive content of various seaweed species (Holdt & Kraan 2011; Schiener et al. 2015; MacArtain et al. 2007), relatively few studies on preservation techniques and their impact on the valorisation of valuable compounds are undertaken. Furthermore, very little information is available concerning the stability of biomass following primary processing such as drying, freezing and ensiling. Some research projects addressing these issues are underway in Norway.

IV - RECOMMENDATIONS ON SEAWEED CULTIVATION

WHAT IS CULTIVATED?

Define the need: Before growing a new species, the traits of interest should be identified, and the species relevance to the market assessed. A seaweed should only be grown if economic and financial interests exist.

Define the resource: Mapping of the biological material available along European coasts will provide tools to characterise resources in the vicinity of each potential farm.

A need to control the transfer of a resource from one area to another. Sourcing requires the identification and characterization of local seaweed species, and specifically for at-sea systems.

In land-based systems, non-native species/non-local populations can be cultivated but within a well-defined framework. Cultivation systems must ensure optimal treatment of discharged water in order to avoid any dispersion in the wild marine ecosystem.

In at-sea systems, only local populations from native species or cultivars/strains selected from crosses between local genetic variants should be cultivated until the population dynamics and population genetics are better understood for each cultivated species. However, the definition of a local population is a relative concept based on the genetic diversity and the existence of connections (i.e. gene flow) between the individuals making this population compared to other populations of the same species which are geographically distant (see definition in glossary). Data are still missing to be able to assess it for most seaweeds.

New importation of species outside Europe should be prohibited for at-sea cultivation or open systems, such imports should be overseen for land-based confined systems.

Build collections of strains from all original wild populations and strains from cultivated populations. This to keep a backup of the different productions, which can then be used for selection programmes.

It is advisable for each country to develop structures such as breeding nurseries for producers. At the local/national level, structures could be set up to ensure the sovereignty of what is produced: collection of stock. Therefore, technical centres of reference should be implemented in order to manage collections of strains and supply producers with locally-adapted seeds. Such centres should not be independent of the stakeholders of the sector, but rather be managed and headed by collaborating scientists, state representatives and seaweed farmers. In Europe, a transparent database listing experts and regional/national entities would provide access to technical and decision-making centres for each country/region.

Implement tools to ensure the traceability of all cultivated strains (indicators and procedures). It would be appropriate to homogenise the indicators from one country to another. A consortium of stakeholders should establish a certified protocol and become the community reference providing a space for dialogue and consultation.

GOVERNANCE AND TECHNICAL STRUCTURE

Reference technical centres should be set up with regional expertise to assist local farmers and/or to identify suppliers on request. Each centre should be listed and should follow best practices provided at the European level. As mentioned above, the management body of these centres should include scientists, local state representatives and local seaweed producers/farmers and be connected at the European level.

For any "Red-listed" species, the causes of their local extinction must be identified before implementing any conservation/restoration programme.

At the national level, an integrated governance system should be implemented to support and develop collaboration between technical centres, institutions and producers. It should include local elected representatives and professional representatives specialised in legal/financial (banking)/and insurance sectors. This governance body should be implemented in each country by a group with the means to manage the task at a national level. Such a system would support producers in accessing funds and adequate insurance in the event of vandalism, accidents or natural disasters.

Introduce Certification Consortium structures including all stakeholders of the seaweed-aquaculture sector at the EU level for:

- **Control of the origins of cultivated strains at a national level.** Such certification centres would work in close collaboration with producers and build a database on cultivated strains in order to ensure their traceability whether the strains are shared between different producers or cultivated by only one of them.

- **Standardisation of best practices for seaweed aquaculture.** Such certification centres would regularly reevaluate and update good practices (for example, once every 4-5 years). They will make sure that these good practices are still consistent with the sector's evolution. An example of such a certification centre is the Aquaculture Stewardship Council, ASC/).

CULTIVATED HOW?

Define the geographical limits of what is meant by "local strains". A deeper knowledge of populations and their connections (i.e. gene flow) is needed to identify better the optimal sourcing areas from which farmers should harvest fertile individuals and then produce "local strains".

Control systems monitoring the quality of the water coming in and out should be improved in land-based systems (sterilisation of the water outlet to neutralise spores). Protocols controlling the dispersion of species in at-sea systems must be implemented.

Pest and disease management appears crucial for sustainable development of seaweed aquaculture. Even though many non-indigenous cultivated species are not invasive, they can act as vectors of introduction for pathogens or pest organisms. Toxic invaders can affect human health directly, or else indirectly by accumulation in other organisms that are for example intended for human consumption.

Prevent any reproduction events and/or dispersal from farms to wild populations. Operations related to the reproduction of seaweeds must be driven in confined systems. The cultivation period in open systems must be outside of the species' reproductive period: the harvest of cultivated individuals must be carried out before initiation of the reproductive period.

Non-intensive strategies are recommended and need to be adapted to each species. To this end, intensive cultivation must be defined. Alternative solutions consist in the cultivation of a combination of strains, or of alternating species, or else spatial and/or temporal heterogeneity of cultivation practices. High densities in cultivation systems are expected to prevent the presence of competing species, but they can increase the spread of pathogens. Optimal densities must be adapted to each species.

Preservation methods that *(i)* minimise losses of valuable compounds, *(ii)* ensure product safety, and *(iii)* limit energy use and associated costs, are a key to increasing the industry's profitability.

HOW TO DEVELOP THE INDUSTRY?

Better understanding is required on the number of years of cultivation before benefits are reaped. Factor experiments taking into account temperature, nutrients, salinity and light are needed to identify optimal conditions for growth, biochemical composition or flavour, effort and cost. Since the form and beneficial constituents of the one species can vary according to seasons and geographical regions, attention should be paid to the temporal and geographical distribution of traits of interest (i.e. assess and predict the extent of its variation).

Relevant pre-treatment steps associated with efficient production systems to stabilise post-harvest seaweed biomass and obtain high-quality products that may undergo further conversion steps must be developed.

Efficient stabilisation alternatives and optimal procedures to prepare biomass for chain extraction of high-value components will ensure access to seaweed biomass year-round and support the growing demand for bioactive substances of natural origin and/or marine origin. This will create value in the coastal industry and support the sustainable development of the European bioeconomy based on the cultivation and processing of macroalgal biomass. However, because of the seasonality of the seaweed production, and the currently limited cultivation areas, producers cannot produce more than what they sell in order to build stocks of material and they generally operate in a just-in-time flow.

SUPPORT BASIC AND APPLIED RESEARCH

Better knowledge of the geographical distribution and dynamics of species of interest is needed.

Better understanding of species life cycles is necessary to identify the techniques that enable control of seaweed growth. This includes both the study of the response to environmental parameters and functional studies of genes to understand genetic importance of different processes including development of new individuals, growth, protection against environmental challenges and food and feed quality/safety.

Assessment of the impact on local biodiversity of at-sea systems should be carried out before any cultivation in open systems, including breeding programmes. However, specific methodological tools are lacking for now. Collaborations between research institutes and producers should be promoted.

Conservation techniques and their impact on valuable products require more research.

More knowledge on the benefits of seaweeds dried by alternative technologies (infrared, microwave and superheated steam drying) which are increasingly used in the food industry to improve energy efficiency and product quality.

More understanding of the domestication process which has a significant effect on the diversity of associated organisms (symbionts, pests, diseases...) and the structure of the marine ecosystem. More in-depth knowledge of the life cycles of each species of interest is needed: to be domesticated, a species must be controlled in its reproductive and growth phases *(see chapter VII on Research programmes to support sustainable development of seaweed aquaculture, section Biological and ecological challenges).*

CHAPTER V -

CHALLENGES IN MARKET ECONOMY AND REGULATION

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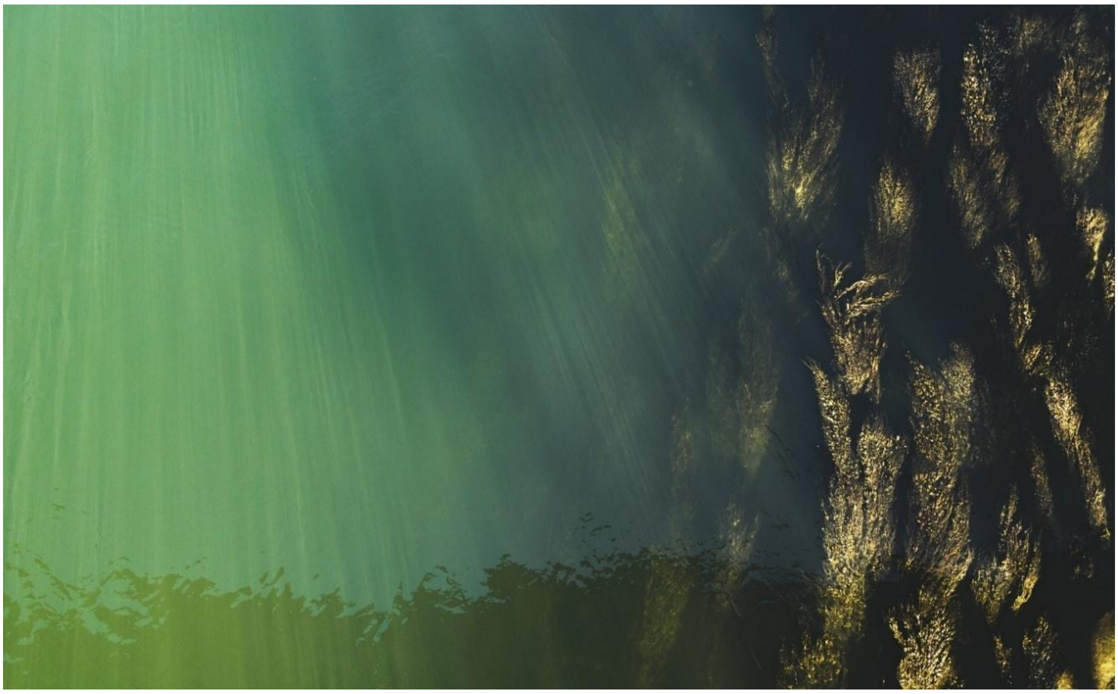

I - RELEVANT EUROPEAN LEGISLATION

Currently, no specific European legislation exists for seaweeds aquaculture although several regulations and recommendations apply to seaweeds, as reviewed in the table below (Table 5) and summarised in Figure 20.

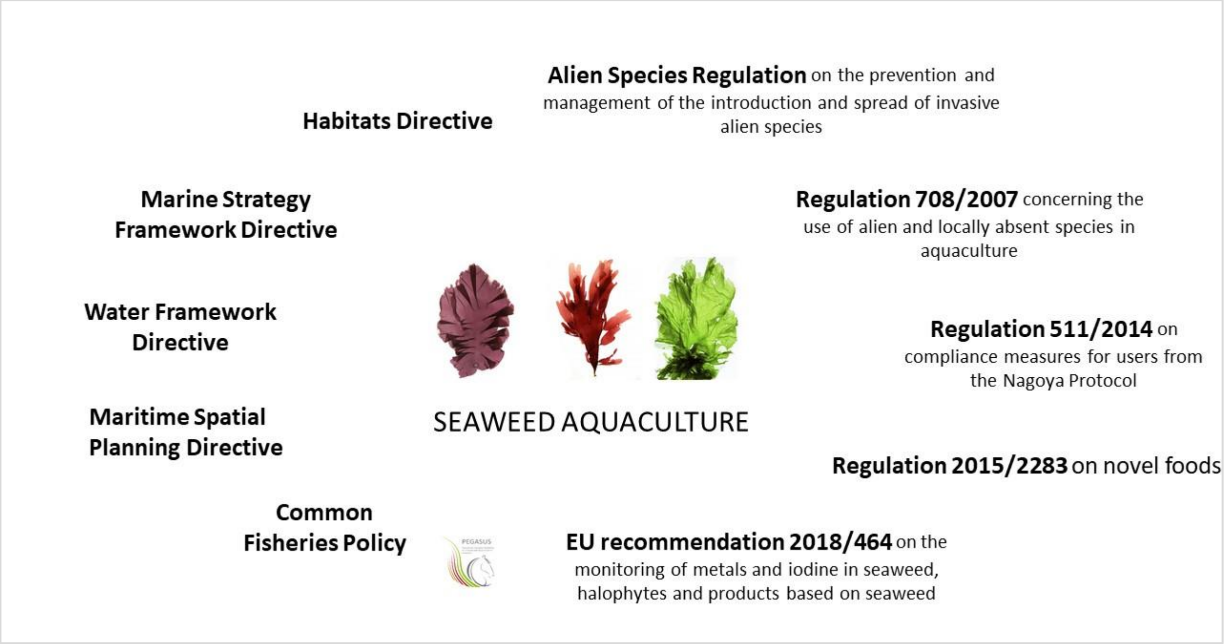

Fig. 20: Different legislations apply to seaweed aquaculture.
(Design: Michèle Barbier, Institute for Science & Ethics)

The section below describes the general objectives of each regulation/recommendation, highlights the topics relating to seaweed aquaculture in particular, and presents specific challenges regarding the application of the legislation to seaweed aquaculture.

Table 5: List of directives and political initiatives related to seaweed aquaculture and the main associated challenges.

Directive/ Political initiative	Objectives	Topics related to seaweed aquaculture	Challenges
Habitats Directive (92/43/EEC) on the conservation of natural habitats and wild fauna and flora	Promote biodiversity by protecting natural habitats and species, contributing to the sustainable development of ecosystems at the EU level.	Natural habitat types of community interest include coastal and halophytic habitats, specifically open seas and tidal areas with reefs.	Aquaculture development should be compatible with natural habitats and biodiversity protection.

Marine Strategy Framework Directive (MSFD)(2008/56/EC, CD 2017/848) establishing a framework for community action in the field of marine environmental policy	Achieve and maintain Good Environmental Status of the EU marine environment by 2020.	Descriptor 1 (Biodiversity): Benthic habitats including rock and biogenic reefs, Descriptor 2 (Invasive species) including macroalgae, Descriptor 5 (Eutrophication) with criteria on macroalgae (opportunistic macroalgae and macrophyte communities), and Descriptor 6 (Sea-floor integrity) considering the structure and functioning of intertidal ecosystems	Aquaculture development should not negatively affect biodiversity and intertidal ecosystems, should not contribute to the introduction of invasive species, (assessment of established non indigenous species is not a primary criteria) and should not contribute to eutrophication in marine waters (coastal areas and open sea).
Water Framework Directive (WFD)(2000/60/EC) establishing a framework for the protection and enhancement of good status of inland surface, transitional, coastal and ground water	Achieve Good status of waters by maintaining a framework of biological and physicochemical quality elements at a certain level of quality status.	Macrophytes and phytobenthos are one of the three biological quality elements assessed under the WFD. Nutrient enrichment is one of the non-biological quality elements assessed under the WFD.	Aquaculture development should not negatively affect the biodiversity of macrophytes and phytobenthos or increase eutrophication in coastal waters.
Maritime Spatial Planning Directive (2014/89/EU) establishing a framework for the planning of multiple uses of maritime and coastal areas	Application of an ecosystem-based integrated approach to spatial planning of the maritime environment, ensuring the sustainable economic development and ecological protection of maritime and coastal areas.	The use of maritime space for multiple purposes (e.g. ecosystem and biodiversity conservation, aquaculture installations and sustainable management of coastal resources) requires integrated planning of space usage by potentially competing activities.	The development of offshore aquaculture implies good management of space use coordinated with other maritime activities.
Common Fisheries Policy setting out rules for the management of fishing fleets while ensuring the conservation of fish stocks	Ensure environmental and socioeconomic sustainability and the safety of fishing and aquaculture activities.	In order to boost the development and competitiveness of the aquaculture sector, and in recognition of the potential of aquatic farming in the EU, a cooperation process was launched at the Union level based on Strategic Guidelines and Multiannual national strategic plans for	At present, the Multiannual national strategic plans for the development of sustainable aquaculture do not mention seaweeds among the main species cultivated per volume but several of these national plans (e.g. France, Ireland, UK and Spain) refer to promoting measures to increase current ongoing cultivation or the need for tailored research and spatial-

		aquaculture (including aquatic plants).	planning initiatives targeting the national seaweed-aquaculture sector.
Alien Species Regulation (1143/2014 EU) on the prevention and management of the introduction and spread of invasive alien species	Ensure that the species listed as invasive alien species of Union concern are not brought, kept, bred, transported, placed on the market, used or exchanged, allowed to reproduce, grow, be cultivated or released into the environment.	This regulation does not apply to species listed in Annex IV of Regulation 708/207 when used in aquaculture.	The list of alien species of Union concern currently does not include any marine species. The national lists of invasive alien species of Member State concern include seaweed species but the harmonization across Member States should be promoted.
Regulation 708/2007 concerning the use of alien and locally absent species in aquaculture	Develop a framework at Union level to ensure adequate protection of aquatic habitats from the use of alien and locally absent species in aquaculture.	The regulation should cover all aquaculture activities, all alien and locally absent organisms farmed, and all forms of aquaculture. Activities related to the use of certain alien species long cultivated by aquaculture should benefit from different limitations.	This regulation is not fully applied to the alien and non-local species listed in Annex IV of the regulation. No seaweeds are listed in Annex IV.
Directive 2011/92 EU and its amendment 2014/52/EU on assessment of the effects of certain public and private projects on the environment	Establish and harmonise procedures for environmental impact assessment (EIA) of private and public projects, contributing to high-level protection of the environment and human health.	A complete assessment of a project's likely effects on the environment should be carried out before it being granted consent. Aquaculture is included in Annex II, listing the projects that might be subjected to EIA depending on Member States judgement.	Annex II details, under the category "Agriculture, Silviculture and Aquaculture", the subcategory "Intense fish farming" but no reference is made to seaweed farming.
Regulation 511/2014 on compliance measures for users from the Nagoya Protocol	The Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilisation in the Union is a treaty adopted by the Convention on Biological Diversity. This regulation aims to create a framework to increase cooperation between stakeholders involved in access to and benefit-	Any genetic resource (meaning genetic material, i.e. any plant material containing functional units of heredity) and traditional knowledge associated with genetic resources used shall be accessed in accordance with the terms of the regulation.	The situation regarding cultivated genera and the protection of genetic resources is unclear. Does it apply within national jurisdictions? Seaweeds cultivated offshore could be considered as being located in areas beyond national Jurisdictions (ABNJ).

	sharing for genetic resources		
Regulation 2015/2283 on novel foods	Establish updated rules for novel food, amending Regulation 1169/2011 and repealing Regulations 258/97 and 1852/2001. Consider the developments in Union law and scientific and technological progress.	This regulation applies to novel foods. The term “novel food” applies to all the seaweed species produced for food (or food supplements) that were not used for human consumption to a significant degree within the Union before 15 May 1997.	Novel food should not be placed on the market or used as food for human consumption unless it is included in the Union list of novel foods authorised to be commercialised within the Union. Up to now, regarding seaweed, the products included in the list are *Ecklonia cava* phlorotannins and fucoidan extract from *Fucus vesiculosus* and *Undaria pinnatifida*.
EU recommendation 2018/464 on the monitoring of metals and iodine in seaweed, halophytes and products based on seaweed	To monitor the concentrations of arsenic, cadmium, iodine, lead and mercury in seaweeds and halophytes in order to establish maximum levels.	The Member States, in collaboration with food and feed business operators, should monitor, during the years 2018, 2019 and 2020, the presence of arsenic, cadmium, iodine, lead and mercury in seaweed, halophytes and products based on seaweed, and report these values to EFSA.	Although a list of seaweed species authorised as food is currently available, it is not clear whether certain species (e.g. *Codium* sp.) listed as targets for monitoring, are authorised as food within the Union. Arsenic-level detection in seaweeds is of concern.

II - NATIONAL AQUACULTURE REGULATIONS AND STRATEGIC PLANS

The national regulatory framework and the current status of development of the seaweed-aquaculture sector are described for seven of the European countries. The main challenges to meet for sustainable development of the seaweed-aquaculture industry at the national level are also identified for these countries.

II.1. Norway

II.1.1 AQUACULTURE AND SEAWEED-SPECIFIC REGULATION

In Norway, there are currently no specific regulations for seaweed aquaculture, but as for all other forms of aquaculture, seaweed are regulated by the Aquaculture Act. This act provides several general regulations, including that aquaculture is only authorised if it is carried out in an environmentally sustainable manner and if all producers operate under an aquaculture license.

Seaweed-aquaculture licenses are granted by the Ministry of Trade, Industry and Fisheries. For areas > 10 ha, license holders are required to perform environmental surveys to document that their production is environmentally sustainable.

II.1.2 CURRENT SITUATION

Significant cultivation trials and breeding experiments with brown seaweed have been conducted in Norway since 2013/14. The first large-scale farms were built, and concession requests rose significantly from just a few before this period, to several tens (more than 40) by 2016/17. Ever since, their cultivation has taken up dynamic growth. Production is mainly targeting *Saccharina latissima* and *Alaria esculenta* for the food market, and production levels were up to 100 tons per farm by 2017/18. Given the data reported by the Directorate of Fisheries (2016) for the year 2015, the retail values of *S. latissima* and *A. esculenta* were €350 t^{-1} and €965 t^{-1}, respectively. Although no information is available regarding the retail markets of the produced biomass, *A. esculenta* is often sold in dried or fresh form as a high-value food ingredient or sea vegetable whereas *S. latissima* has a broader range of market outputs, e.g. dried for human consumption or as animal feed. This difference in usage may explain the difference in market value. A higher value for *A. esculenta* may also result simply from a lower biomass availability on the market. In comparison, the retail value of global seaweed production output in 2014 was estimated to €181 t^{-1} based on figures mentioned earlier (FAO 2016).

II.1.3 CHALLENGES

There are several key issues that need to be addressed in order to evaluate possible environmental impacts of seaweed farms and the carrying capacity (indicators/thresholds) of sea areas:
Genetics: The use of local strains versus breeding to upscale and industrialise.

- Benthic: Sedimentation/effect on benthos from seaweed farms.
- Pelagic: Uptake of dissolved nutrients/competition with microalgae and other food chains (and positive CO_2 uptake and storage).
- Licenses: The process to apply for a license should be facilitated, especially when a site must be tested prior to cultivation. This would reduce the application-processing time.
- Standardisation: Standardisation of seaweed farms/cultivation technologies, similar, for example, to "Norwegian Standard" for salmon farms, which aim to prevent severe damage and loss of fish and farms.
- Additional general challenges are lack of: educated personnel for such aquaculture; scaling up of the activity for harvesting and conservation of fresh biomass; understanding the market; solid

knowledgebase of environmental impact of large-scale seaweed cultivation at sea including the effect on biodiversity and/or, when in IMTA, the effect on the salmon; availability of marine space for aquaculture; production costs; stability in crop yield; limitations on potential due to restrictions on domestication/breeding in Norway; lack of clarity about the legislation for organic certification.

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II.2. France

II.2.1 AQUACULTURE AND SEAWEED-SPECIFIC REGULATION

In France, the only specific regulation concerning seaweed aquaculture is an official list of authorised species. Besides this list, seaweed cultivation follows the same framework as other aquaculture activities (fish and shellfish production).

Three levels of regulation are to be considered for every new farm settlement or the cultivation of new species:

- National regulation (law): Determines the conditions under which activities are authorised on the maritime public domain:

- Activities for exploitation of the lifecycle of marine plant or animal species, including capture, rearing, maturing, purification, storage, packaging, shipping or first-time marketing products (Article 1, 1st paragraph).
- Activities of marine aquaculturists (...) when carried out on plots of the State’s public domain (Article 1, 2nd paragraph).

- Departmental/territorial regulation: The Strategy of Departmental Structures for Marine Aquaculture defines the management policy for marine farming operations to ensure the economic viability of enterprises. It also defines, by production area and by type of crop, the exploitation and management methods for the public maritime domain assigned to marine cultivation.

- Local regulation: The SMVM (Scheme for Enhancement of the Sea) is a document for the management of coastal areas, which specifies the purpose of these areas and ensures consistency between their different uses, in particular between protection of the environment and economic development. It also aims to define the conditions for balanced development of both terrestrial and maritime parts of the coastline.

Each new “Official Application for Authorisation to Exploit Marine Crops” must be studied and validated by the Territorial Authority. The different steps for the procedure are nevertheless complex and time-consuming because the number of forms and files to complete is high, as well as the number of recipients organisations.

II.2.2 CURRENT SITUATION

Concerning the Brittany territory, 30 species are authorised for at-sea cultivation:

- Brown algae: *Alaria esculenta, Ascophyllum nodosum, Chorda filum, Fucus vesiculosus, Himanthalia elongata, Laminaria digitata* (Kombu), *Laminaria hyperborea, Laminaria japonica* (Kombu), *Laminaria ochroleuca, Padina pavonica, Pelvetia canaliculata, Saccharina latissima* (Kombu royal), *Saccorhiza polyschides, Undaria pinnatifida* (Wakame), *Fucus serratus, Fucus spiralis*.

- Red algae: *Asparagopsis armata, Chondrus crispus* (Pioca), *Gracilaria verrucosa* (Ognori), *Laurencia obtusa, Lithothamnium calcareum* (Maërl), *Palmaria palmata* (Dulse), *Porphyra dioica* (Nori), *Porphyra laciniata* (Nori), *Porphyra leucostica* (Nori), *Porphyra purpurea* (Nori), *Porphyra umbilicatis* (Nori), *Dislea carnosa.*

- Green algae: *Cladophora sp., Ulva sp*.

However, specific recommendations are regularly updated by the CSRPN (Regional Scientific Council for Natural Heritage). For example, about the cultivation of Wakame (*U. pinnatifida*), the Scientific Council recommends: i) prohibiting any new concessions in Brittany, and ii) maintaining *U. pinnatifida* crops in already-cultivated areas if long-established farmers, while monitoring their aquacultural practices and abstaining from experiments with new ones, experience no setbacks. Another example is the at-sea cultivation of *Ulva sp*. The CSRPN recommends that it not be authorised because of the enormous phenomenon of the green tide that has been prevalent for several decades along the entire Breton coast. While only three species (*S. latissima, A. esculenta* and *U. pinnatifida*) on offshore farms and two species (*Ulva sp*. and *Chaetomorpha*) in land-based systems are commonly cultivated, new species are under trial for development in the future (e.g. *P. palmata, Porphyra sp.*, *Codium tomentosum*).

II.2.3 CHALLENGES

- Access to information about the regulatory framework.
- Simplification of the procedures.
- Social acceptability.

II.3. Scotland

II.3.1 AQUACULTURE AND SEAWEED-SPECIFIC REGULATION

The Scottish Government initiated a consultation process for seaweed policy in 2013, which involved some public bodies such as the Food Standards Agency (FSA), the Scottish Environment Protection Agency (SEPA) and Scottish Natural Heritage (SNH). This led to the Scottish Government’s publication of the Seaweed Cultivation Policy Statement (SCPS).

Other relevant policies applicable in the UK as a whole include “Safeguarding our Seas” (DEFRA 2002), which presents the government’s vision for marine-environment policy. In response, a set of high-level policy objectives were prepared by “Our Seas - a shared resource” (HM Government 2009), which describes the responsibilities of devolved administrative bodies. After the introduction of these high-level objectives, the Scottish Government introduced the Marine Scotland Act (2010), a framework for managing Scotland’s marine environment. Part 3 of this act included the development of a National Marine Plan (NMP), which now sets national objectives for sustainable aquaculture, including seaweeds and IMTA. Currently, regulation of seaweed farming in Scotland is underpinned by the consenting process, which is informed by the policies outlined in the SCPS, and categorises scale of production as either “small-medium" (0-50 x 200m lines) or “large" (>50 x 200m lines). The SCPS states that there is support for "small-medium" farms under this definition and will be subject to regulatory considerations and policies included in Chapter 4 of Scotland’s National Marine Plan (NMP). There is some debates whether stocking density or tons production would better define the scale of seaweed farming as these may be more scalable with environmental changes. Regional Marine Plans are currently in development to provide Marine Spatial Planning with a more granular scale than the NMP. The creation of regional marine plans involves a deliberative process with local stakeholders and aims to balance the many uses and designations of the marine environment in an adaptive way, including the potential for seaweed cultivation. Each Regional Marine Plan will be tailored to suit the priority industries and activities in those areas.

In order to obtain legal consent for an aquaculture activity in Scotland, there are two permissions that must be acquired: *i)* a license from Marine Scotland - Licensing and Operations Team (MS-LOT), underpinned by legislation through the Marine Scotland Act (2010), which governs activities that create deposits in, on or under the seabed, and *ii)* a lease from the Crown Estate (Wood et al. 2017). Seabed leases are authorised by The Crown Estate Scotland (CES), and the leasing process for seaweed cultivation falls under The Crown Estate Scotland Bill (2018). The CES sees "commercial potential for seaweed farming*" and* is currently exploring opportunities to support local and community-owned sites. Also, some specific regulations apply on Shetland and in parts of Orkney, for the obtention of "Works Licenses" from local authorities in order to ensure that activities do not interfere with navigation within harbour or port areas.

The location of permitted seaweed-cultivation sites is recommended in the SCPS as being within designated shellfish waters (The Water Environment (Shellfish Water Protected Areas: Designation) (Scotland) Order 2013), which are managed to reduce the contamination risk of harvesting shellfish for human consumption. The general assumption made here is that cultivating seaweed in "clean" waters will reduce potential contamination risks to consumers. However, the relationship between environmental contaminants and food safety are yet to be established. This is particularly true for some heavy-metal contaminants such as arsenic, which is not currently monitored in the context of seaweed. A stronger evidence base will be required to establish the most suitable locations for cultivating seaweed and should be developed in parallel with the setting of appropriate standards for consumers. These areas are assessed and classified by the SEPA in order to protect the harvestability of products for human consumption under a set of environmental objectives. Despite there being no specific legislation for the monitoring and regulation of seaweed-cultivation sites, in order to be granted a license the following assessments may be required: Environmental Impact Assessment, Habitats Regulation Appraisal, Marine Protected Area Appraisal, Water Frameworks Directive and Navigational Marking of the Site Assessment. Under the Environmental Impact Assessment Directive (97/11/EC), seaweed cultivation is not listed in Annex I or II and thus does not automatically requires an EIA to be undertaken. For the Habitats Directive, MS-LOT may request an assessment of whether the site could impact designated sites (e.g. Ramsar, Natura 2000, Special Areas of Conservation and Special Protection Areas). If a proposed site has the potential to impact an MPA, then under the Marine Scotland Act (2010), Marine Scotland will seek the independent advice of Scottish Natural Heritage on whether designated features will be impacted and if this can be mitigated. An assessment under the WFD directive is required up to one nautical mile if the site risks deteriorating water quality in the area and compromising the meeting of WFD objectives. However, current cultivation practices used in Scotland are unlikely to deteriorate water quality significantly to undermine WFD objectives. Although there is no specific legislation to enact monitoring of environmental impacts, there have been recommendations in the consultation of seaweed policies that seaweed cultivation is included in The Aquaculture and Fisheries (Scotland) Act 2013; as yet however, there have been no further developments on its inclusion in this legislation. If it were to be included, the licensing process would be likely to require planning permission from local authorities under the Town and Country Planning (Scotland) Act 1997. Developments which fall to local authorities for permissions are required to follow Scottish Planning Policy, which necessitates full consultation with local communities during the planning process and promotes consultation with local communities before the submission of a planning application.

II.3.2. CURRENT SITUATION

The seaweed-cultivation sector is currently limited to pilot-scale farms in Scotland either for small-holder/community purposes or for research. The species which are cultivated routinely include *Saccharina latissima* and *Alaria esculenta*. Species cultivated on a smaller scale include *Laminaria digitata*, *Sacchoriza polyschides and Laminaria hyperborea* (Kerrison et al. 2016). Species used in small-scale experimental trials include *Ulva* spp., *Palmaria palmata* and *Osmundea pinnatifida*.
The growing techniques currently utilised include long-line and grid-based systems. Traditional methods of hatchery-reared twine seeding produce the most reliable results. However, directly seeded fabrics are being tested and developed to address the cost limitations of hatchery-reared twine. Out-planting occurs in early autumn when the surface-water temperature drops while nutrients increase after summer (September/October) and harvesting occur in the late-spring to early-summer months (May/June) before sun-bleaching and biofouling significantly destroy crops.

II.3.3 CHALLENGES

- Social acceptability, particularly in the licensing process.
- Availability of marine space for cultivation.
- Clarity over who will regulate sizeable farms and what the ongoing monitoring process should be after licensing.
- Cost of production. Cultivation requires mechanised seeding and harvesting with mooring and cultivation systems that minimise cost.
- The requirement for summer crops (*Ulva* and bivalves are being considered) which have a lower susceptibility to biofouling and outbreaks of grazing organisms.
- Reduction of the impact of huge variability in growth/harvest success from year to year, based on site-specific climatic influence and environmental variability.
- Genetic resources are largely understudied, limiting our ability to manage crop success (e.g. disease resistance/growth).

II.4. Portugal

II.4.1 AQUACULTURE AND SEAWEED-SPECIFIC REGULATION

In Portugal, there is no specific legislation on seaweed aquaculture, and the activity is regulated by the Legislative Decree 40/2017 defining the regime for the establishment of aquaculture facilities in marine, transitional and interior waters. This legislation addresses promotion of the sustainable development of aquaculture in the context of the Blue Economy, and the simplification of procedures related to the licensing and operationalisation of aquaculture facilities. While it refers specifically to the diversification of organisms produced and to the promotion of offshore aquaculture, there is no particular mention of seaweed aquaculture.

Similarly, in the Autonomous Region of Açores, there is no specific legislation for seaweed aquaculture, and the general aquaculture regulatory framework regulates the activity. The Regional Legislative Decree 22/2011/A (4 July) specifies the conditions for the installation and exploitation of aquaculture facilities with commercial purposes within the land or maritime space of Açores. The competent authorities need to grant companies the respective title of use of water resources prior to the installation of the aquaculture facilities. The legal framework is being revised to streamline the administrative procedures involved and to attract investment in aquaculture.

Following the Resolution of the Government council no 126/2016 (25 July), revised by the Resolution of the Government council no 2/2018 (24 January), pre-defined areas for aquaculture production on the islands of Faial, Terceira and Sao Miguel were created based on the mapping of coastal and offshore areas with socioeconomic, environmental and administrative potential. These areas, where the production of algae, invertebrates, fishes, crustaceans and molluscs is allowed, have a licensing period of ten years and are exempt from pre-installation authorisations.

It is also possible for aquaculture and marine biotechnology projects that foresee the creation of at least three jobs to benefit from additional financial support of 30%. This support can rise to 40% if highly qualified workers are hired.

II.4.2 CURRENT SITUATION

At present, three aquaculture companies are operating in Portugal, two being land-based and one offshore (at a pilot scale). The species currently produced at a commercial scale are mainly *Ulva* sp.

Initial - and not very comprehensive or well-documented - trials of offshore farming of *Saccharina latissima* were conducted in 2012 in the Peniche area in the Centre region, as well as in the North, off Aguçadoura. These trials showed promising growth but relatively early colonisation by epiphytes, despite the trial sites being fully exposed with significant wave action. In 2015/16 and 2016/17, trials for growing *Saccharina latissima* and *Laminaria ochroleuca* on an oyster farm were conducted with mixed results (Azevedo et al in press). Due to a lack of resources for systematic trials and a lack of near-term economic-feasibility outlook justifying private investments at this phase, Portuguese offshore cultivation trials have been paused until solid financing is available.

In the Autonomous Region of Açores, there are currently five projects at their installation phase in the area, for algae, fish and sea-urchin production.

II.4.3 CHALLENGES

- Use existing fish/animal aquaculture farms that can accommodate seaweed tanks/raceways to start seaweed cultivation at (applied research) pilot scale or commercial scale to use already existing main infrastructures for cultivation and services (commercialisation); demonstrate the potential of such activity and also create co-benefits for the fish farm.
- Start using species already known (main cultivation requirements) by local staff (researcher or entrepreneurs involved) and with potential commercial value to test the system and set up cultivation conditions and routines, train staff and produce biomass to demonstrate the concept.
- Domesticate local species as is already done in other countries, to facilitate their introduction to some markets (e.g. food).

II.5. Denmark

II.5.1 AQUACULTURE AND SEAWEED-SPECIFIC REGULATION

Licensing of seaweed-cultivation sites is handled by the Danish Coastal Authorities (DCA), whereas for licenses to cultivate mussels or finfish, the Danish Agricultural Agency (DAA) is responsible. This division of responsibility for mariculture crops complicates the process of obtaining licenses for IMTA in Denmark. Licenses for seaweed cultivation can presently be obtained for five years only since the DCA need more knowledge on the long-term effects of large-scale seaweed cultivation on the marine environment. However, this short licensing period limits the willingness to invest in seaweed cultivation. Regulations presently include guidelines for the production of organic sugar kelp, and a law (L111, 2017) enabling finfish producers to expand their production if nutrient emissions (N and P) deriving from surplus fish production are removed through the cultivation of compensation crops, namely mussels or seaweed.

In Denmark, the environmental authorities are closely following developments in seaweed cultivation, since the nutrient-uptake capacity of seaweed cultivation comprises an instrument for actively removing excess nutrients in eutrophic marine environments, where the standards for good ecological status (GES) set by the WFD and by the MSFD are not yet met.

II.5.2 CURRENT SITUATION

In Denmark, up to 10 tons of wet sugar-kelp biomass is produced on an annual basis, primarily for the food market and research purposes. The cultivation systems used are mainly long line systems for mussel cultivation, with seaweed lines attached in continuous loops or as single droppers exploiting the full photic zone. Average annual yields range between 1-4 kg of fresh seaweed per meter of seeded line (Moller-Nielsen et al. 2016). In the Faroe Islands, more robust offshore systems (MACR rigs) have been developed, producing yields that are considerably higher. This is because seeded lines may be harvested several times a year (Bak et al. forthcoming). In 2017, four licenses for seaweed cultivation were active in Denmark, and the largest commercial player is Hjarnø Havbrug, yielding 100 ha in organic sugar-kelp production since 2011. Two of the active licenses are for research purposes. At the Faroe Islands, the major commercial player is Ocean Rainforest. National and EU research projects are currently gathering knowledge to fill the most prominent knowledge gaps: impacts on local hydrodynamics, natural benthic vegetation, local biodiversity, nutrient and GHG (Greenhouse gas) balances, marine birds and mammals.

II.5.3 CHALLENGES

Several challenges should be addressed over the coming years in order to promote seaweed cultivation in Denmark:

- Site selection: Documentation on what types of marine areas will sustain optimal yields, not only in terms of biomass, but also specific valuable compounds such as sugars, proteins, and bioactives, and which sites will sustain the highest efficiency of nutrient recapture, and also the highest impact in support of the environmental goals set by the EU WFD.
- Selection of optimal local ecotypes and/or development of breeding programmes: Aiming for higher yields of biomass and desired compounds, as well as for resilience against stress factors such as low salinity, high temperature and high fouling pressure.
- Documenting the effects of large-scale cultivation on the marine environment (i.e. local hydrodynamics, natural benthic vegetation, local biodiversity, nutrient and GHG balances, marine birds and mammals) will help authorities to grant licenses for longer periods.
- Establishing more transparent legislation on licensing and organic certification for seaweed cultivation.

II.6. Republic of Ireland

II.6.1 AQUACULTURE AND SEAWEED-SPECIFIC REGULATION

To cultivate seaweed in the Republic of Ireland, an aquaculture and foreshore license administered by the Aquaculture and Foreshore Management Division of the Department of Agriculture, Food and the Marine (DAFM) is required. In Ireland, aquaculture is licensed under the Fisheries (Amendment) Act, 1997, and its associated Regulations. Ireland's National Strategic Plan for Sustainable Aquaculture Development (DAFM 2016) aims to sustainably grow Irish seaweed production by providing grant aids and special incentives to new entrants to the sector.

II.6.2 CURRENT SITUATION

The wild-seaweed harvesting sector in Ireland is currently worth ~€18 million (BIM 2012). The cultivation of aquatic plants, predominantly marine species of seaweeds, has the potential to support this already well-established industry. The FAO (2017) reports that the Irish cultivated-seaweed sector is worth €50,000-150,000 annually and it is expected to increase further in 2018 according to the 2018 Aquaculture Survey (BIM 2018).

For the past twenty years, most farmed seaweeds have been at research or pre-commercial phase in Ireland, although *Alaria esculenta* has been cultivated commercially for the last ten years. In the period 2010-2016, Ireland produced ~350 tons of farmed seaweeds (FAO 2017), mainly *Alaria esculenta* and *Saccharina latissima*. Both of these are economically attractive species, which are used for human consumption, animal and macroalgivore feed, and cosmetic products. It is expected that farmed seaweed production will increase considerably over the coming years due to the significant number of new entrants applying for seaweed-aquaculture licenses.

In Ireland, marine finfish and shellfish licenses account for approximately 94% of licenses issued, with seaweed aquaculture accounting for 1% of licenses. Currently, there is a small number of aquaculture sites licensed for seaweed cultivation in Ireland, and excess of 20 new seaweed aquaculture applications awaiting determination. Between 2005 and 2016, there were less than ten seaweed aquaculture consents in circulation. However, Ireland's largest commercial-operating seaweed farm (18 hectares) - Dingle Bay Seaweed in County Kerry, established in 2009 - is considered one of Europe's largest commercial seaweed farms.

II.6.3 CHALLENGES

Ireland's seaweed-aquaculture sector shows enormous potential for its production to grow sustainably. However, despite this potential, major challenges need to be met for the country to catch up with global aquaculture leaders. Ireland's aquaculture sector is hampered by an inefficient and complex licensing process, in urgent need of reform. Delayed or lengthy licensing times have proven difficult for businesses to plan accordingly. The capital costs of setting up a cultivated-seaweed farm are high while public acceptance of aquaculture remains a key challenge.

II.7. Spain

II.7.1 AQUACULTURE AND SEAWEED-SPECIFIC REGULATION

Aquaculture in Spain is mainly regulated by the regional governments that have authority over aquatic activities, but also by a set of basic general legislation issued by the central government.

The basic legislation from the central government that affects aquaculture comprises:

i) Law Nº 23/1984 on marine farming (BOE 1984), establishing the regulation and planning of marine cultivation in Spain;

ii) Law Nº 22/1988 on coasts (BOE 1988a), determining the protection, use and control of the marine coastline.

iii) Other legislation affecting aquaculture activities are Law Nº 22/1988 regulating the procedure for Environmental Impact Assessment (EIA) and Royal Decree Nº 630/2013 establishing the forbiddance of alien species aquaculture. Although the EU list of invasive species does not include any seaweed species, the Spanish catalogue of invasive alien species includes different seaweeds with potential interest for aquaculture such as *Gracilaria vermiculophylla*, *Codium fragile* subsp*. fragile*, *Asparagopsis armata*, *Grateloupia turuturu* and *Undaria pinnatifida*.

The legal framework for each of the regional governments may differ; details are given below regarding the regions where seaweed cultivation is currently underway: Galicia (northwest Spain), Asturias (northern Spain) and Andalusia (southern Spain). In these regions, the main regulations in force are:

- Autonomous community of Galicia: Law 11/2008 (modified by Law 6/2009) regulates fishing activities in Galicia and the planning of cultivation facilities. Areas named “culture polygons” were established to mark locations where marine aquaculture should be developed. Procedures follow Decree Nº406/1996 for the establishment of cultivation facilities at sea and Decree Nº274/2003 for inland cultivations. Article 47 of Decree Nº406/1996 refers to seaweed culture, establishing a maximum length for cultivation lines (4000m) with a minimum separation between lines of 1m. This constitutes the only specific reference to seaweed culture in Spanish legislation on aquaculture.
- Autonomous community of Asturias: Law 2/1993 on maritime fishing in interior waters and exploitation of marine resources.
- Autonomous community of Andalusia: Law 1/2002 on the planning, promotion and control of maritime fishing, shellfish exploitation and marine aquaculture.

In the regulations of Asturias and Andalusia, recommendations are made to use denominated “areas of interest for marine aquaculture” - areas considered to meet less conflicts in spatial uses with other activities or to have less environmental limitations.

The transport of individuals and spores for cultivation or any experimental research requires specific authorisation by the autonomous communities and necessitates compliance with sanitary requests. Although these limitations are not specifically established for algae, usually declarations are made to guarantee that they are not affected by diseases or accompanying species that might negatively impact the surrounding environment.

Imports and exports of spores or individuals of species for marine aquaculture require preliminary authorisation by the Ministerio de Agricultura, Pesca y Alimentación and by the autonomous community. If this import pertains to non-native species in relation to Spanish waters, positive technical advice from the Spanish Institute of Oceanography is required.

II.7.2 CURRENT SITUATION

Experimental cultivation of seaweeds on a commercial scale is underway in the three autonomous communities mentioned above: Galicia, Asturias and Andalusia.

- In Galicia there are at least three authorisations for offshore cultivation of *Saccharina latissima*, which initially also included *Undaria pinnatifida* (since forbidden). These cultivation sites are located inside the Galician Rias in specific aquaculture areas where intensive cultivation of mussels is also taking place. Galicia also holds an inland cultivation facility, mainly of Saccharina *latissima* but also of *Gigartinales* and *Ulva* sp.

- In Asturias there is the need for authorisation for the offshore cultivation of *Saccharina latissima*.
- In Andalusia, seaweed cultivation is occurring in earthen ponds for *Ulva* sp., *Gracilaria* sp., *Gracilariopsis longissimi* and *Chondracanthus teedei*.

II.7.3 CHALLENGES

The development and growth of seaweed aquaculture in Spain are limited by different technical, legal and environmental factors detailed below:

- The technology for industrial-scale cultivation of *Saccharina latissima* has already been developed and successfully tested in the Atlantic waters off the northern coast of Spain (Peteiro et al. 2016a). Although there is high interest from seaweed companies to cultivate this species, sea cultivation is restricted by the unavailability of seedling string (juvenile sporophytes attached to strings) as no companies can carry out this process in Spain. Seedlings from other countries (e.g. France) have been imported, but the import was complicated by additional technical and financial issues as well as environmental restrictions.
- Knowledge and technology needed for the commercial cultivation of some species with high commercial interest exist, but the low availability of wild stocks is an issue yet to be tackled. This is the case of *Porphyra sp*. and *Palmaria palmata*, for which knowledge on biology and cultivation is available at the laboratory scale, but no technology to upscale production to a commercial level.
- Environmental restrictions and a lack of legal framework for the cultivation of non-native seaweed species with commercial interest. On the Spanish coast, *Undaria pinnatifida* was successfully cultivated at a commercial scale in Asturias and Galicia with the support of national and regional programmes. Two decades after its introduction, it was included in the Spanish list of alien species precluded from cultivation. An assessment of the potential environmental impacts of alien species and the introduction of locally absent species must be made by an expert committee before their cultivation is formally authorised. This is required before companies obtain legal support.
- There is no specific framework for marine aquaculture which considers the specific needs of seaweed cultivation. Therefore, there is a need to define the spatial distribution of areas with better conditions for seaweed cultivation, to determine the phytosanitary requirements for seaweed used in cultivation, and to define the regulation procedures for the introduction of seaweed strains from other regions.
- Institutional support to streamline bureaucratic procedures and to boost the development of aquaculture is needed. This will diminish pressure on the extraction of wild-stock biomass.

III - COMMERCIALISATION

The main barrier to the commercialisation of seaweeds as mainstream food products is the lack of high consumer demand due to Western food habits, yet to integrate seaweeds as a food commodity. Although seaweed is rapidly gaining importance in the European food-processing and catering sectors as a specialty food in its own right, total sales volumes remain small, resulting in economies of scale having no significant effect to date.

III.1. Regulatory limitations

Another important aspect is the regulatory limitations which bar some species from entry into the European market. The Novel Food Regulation (EC) 2015/2283 amending (EC) No 258/97 only allows certain seaweeds to be commercialised as food. Edible species not on the Novel Food list and lacking proven consumption habits within the Union before 15 May 1997 may have to undergo lengthy authorisation procedures. An issue particularly discussed in the context of brown seaweeds is its high iodine content and – according to water quality – the possibility of heavy-metal particles or other toxic contamination (see e.g. Bouga & Combet 2015) *(see Chapter VI on Challenges in Food safety).*

Regarding this issue, the new EU recommendation 2018/464 on the monitoring of metals and iodine in seaweed, halophytes and products based on seaweed establishes a list of species in which the concentrations of arsenic, cadmium, iodine, lead and mercury must be monitored.
A competitive disadvantage for European seaweed might be the unequal control levels exerted over cultivated seaweed in European waters and imported products, especially from Asia, where regulation concerning food safety and restrictions to local species is looser. Traceability and certification of locally produced biomass can make an important difference in this context.

III.2. Terminology

In addition, some challenges are raised by the terminology used to date when referring to product mass: while "wet weight" / “fresh weight” (FW) can imply different levels of surface-water, "dry weight” (DW) may refer to remaining water content ranging from less than 5% to more than 15%. In addition, the lack of standardised conversion metrics to transform production biomass based on FW to processed DW biomass is a matter of concern. This conversion is not very relevant when considering commercial uses where the resource is used as fresh biomass (e.g. food consumption) but is very much an issue for uses where the biomass is commercialised dried. The relationship between wet and dry biomass is variable according to the species identity, the season and the individual’s age, and needs to be considered in future studies.

IV - GLOBAL MARKET ANALYSIS

Organic Monitor (2014) estimated the total European market volume for sea vegetables in 2013 at around 3,000 tons (472 tons of dried products) having a value of €24 million. Despite the estimated annual growth of 7-10%, the market for seaweed as a food commodity is still very small. Seaweed food products are ultimately consumed either as consumer products (e.g. snacks, salts, pestos or ready-to-eat salads) sold through retailers (shops, supermarkets or online retailers) or as an ingredient in meals served through the HoReCa (Hotel, Restaurant, Catering) sector.

There is a strong need to communicate the benefits of seaweed as a healthy and sustainable food product, and to understand the mechanisms required to turn it from a marginal existence in the Western diet into a fully accepted food commodity as in Asia. The most important factor for higher market penetration will be the adequacy of production cost, which determines the consumer price of product proteins, minerals, vitamins, etc.

One important factor is to increase and strengthen knowledge about the market needs for ingredients and compounds that seaweed can provide. At the same time, a better understanding of the quantity and quality of specific compounds, as well as their seasonal and geographical variability in different seaweed species is required. It is essential to optimise the product concerning its value on the market. Extraction methods and a comprehensive biorefinery concept are, therefore, the baselines for such exercises, and these have been given priority in recent research programs such as the H2020 GENIALG project (2017-2021) and funding initiatives.

A final aspect regarding the large-scale food market is that the commitment of the processing and distribution industry in the past has been limited by erratic supply, unpredictable quantities and variable quality between lots, all of which are fundamental matters for the food industry. A standardised approach to cultivating and delivering seaweed will only be achieved through production scalability, higher and consistent quality, traceability of origin, and predictable production calendars. It is therefore essential to support upscaling efforts of the raw-material-producing industry.

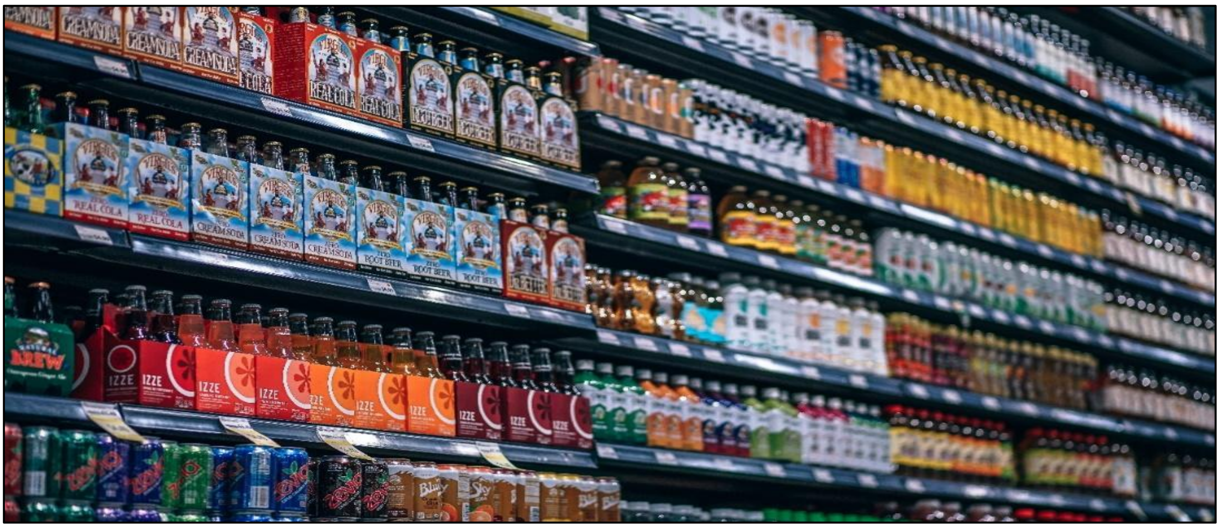

Photo credit: Fancycrave from Pexels

V - RECOMMENDATIONS ON LEGISLATION AND REGULATIONS

Some European legislation and recommendations already consider seaweed-related activities in general and specifically address seaweed regulation (Table 6). Our recommendations concern the following aspects:

- **Aquatic and marine-environment water quality:** A range of legislation addresses protection of the aquatic environment (e.g. Habitats Directive, MSFD, WFD). Aquaculture activities (including seaweed farming) have the potential to affect surrounding communities but also to improve the quality of water through bioremediation by removing nutrients. These aspects should be adequately documented and considered when planning the placement of aquaculture facilities: the potential impact of the cultivated species on the recipient community should be assessed (ecological impact, the introduction of non-local strains, sedimentation effects) and the potential benefits for the quality of the surrounding environment considered (nutrient uptake). The establishment of a framework for IMTA systems is necessary for the development of ecosystem-based management approaches to aquaculture.

- **Maritime Spatial Planning:** Offshore seaweed-farming development and decisions on the location of cultivation facilities should consider the needs of other existing sectors and environmental requirements. A framework for guiding offshore aquaculture spatial organisation, which maximises production by the selection of optimal sites while minimising impacts, should be established.

- **Alien species:** Alien seaweed-species management in aquaculture can be improved by establishing a list of alien species of economic interest in Europe and assessing their risk for the environment. If proven to be of potential risk to native communities, these species must be included in the list of species of Union concern.

- **Seaweeds as food:** An updated and complete list of seaweed species authorised as food in Europe should be compiled. Such a list would facilitate the work of seaweed companies wishing to introduce new products to the market and boost the adequacy of regulations in the seaweed sector and food-security control. Also, the dissemination of this list of species would increase public awareness of the use of seaweeds as food in Western diets, currently one of the main hindrances to the commercialisation of seaweeds as mainstream food products.

- **Licensing:** At the national level, seaweed-aquaculture licensing procedures should be simplified, the transparency and efficiency of procedures increased, and the activity's social acceptability promoted.

- **Standardisation:** A standardised approach to the production and distribution of seaweed products should be promoted at the European scale.

- **Control of imported seaweed products:** Imported seaweed products need to comply with EU or national legislation, and companies should respect common legislation for foods regarding hygiene, labelling etc. Random checks should be carried out on imported as well as national products, which need to comply with EU or national legislation on seaweed as food, food supplements or feed.

Table 6: Specific recommendations for policymakers

	Protection	Regulation, compliance requirements	Recommendations-Governance
SUSTAINABILITY	Environment and Biodiversity	Compliance with Marine Strategy Framework Directive Compliance with Water Framework Directive Compatibility with the Habitats Directive	Based on robust scientific evidence, assess the need to revise EU Regulations 1143/2014 and 708/2007 to include seaweed Support studies to assess the risk of introduced species spreading in the environment (Annex 4 of Regulation EU 708/2007 currently does not include any alien seaweed species) Improve licensing procedures at the national level Implement a framework for traceability Build strain collection centres and support the mapping of local seaweeds Establish a transparent database of expertise/knowledge Update management plans for coastal activities

			Define one single authority for pest & disease management of all marine aquaculture organisms Establish regulation focusing on the spreading of non-local species
COMMERCE	Fair trade	Trade and Access and benefit sharing including seaweeds: Nagoya Protocols	Overcome uncertainties regarding seaweed use in Regulation 511/2014
	Importation		Develop traceability and certification of locally produced biomass Obligation to comply with EU or national legislation on seaweed as food, food supplements or feed
ECONOMY	Production Innovation Market Distribution	Existing Regulation 2015/2283 on novel foods EU recommendation 2018/464	Support automation & mechanisation of farms Update the list of seaweed species authorised as food and make a list available Support development of value-added products, as well as products within food applications Implement regional technical centres for reference and national certification centres Improve the licensing process Support training courses for producers and personnel in the seaweeds sector
	Disease outbreaks		Define phytosanitary requirements Design biosecurity policies and protocols for farm facilities
MANAGEMENT	Maritime space	Maritime Spatial Planning Directive (2014/89/EU)	Consider seaweed aquaculture in coastal management Consider marine space for cultivation Need for a framework for guiding offshore aquaculture spatial organisation, which maximises production by the selection of optimal sites while minimising impacts

CHAPTER VI –
CHALLENGES IN FOOD SAFETY

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Seaweed has long been traditionally used in Asia as food - a practice now spreading to many countries. In France, strong moves have recently been made to introduce seaweed into European cuisine, with some success, although it is still considered an exotic ingredient; in the United States (notably California, Maine and Hawaii), it is found in restaurants and on supermarket shelves. The world is incorporating recipes based on "seaweeds". The current trend of consumers adopting organic, local and "natural" foods from clean environments should further increase seaweed's acceptance and popularity.

Photo credit: Stefan Lorentz from Pexels

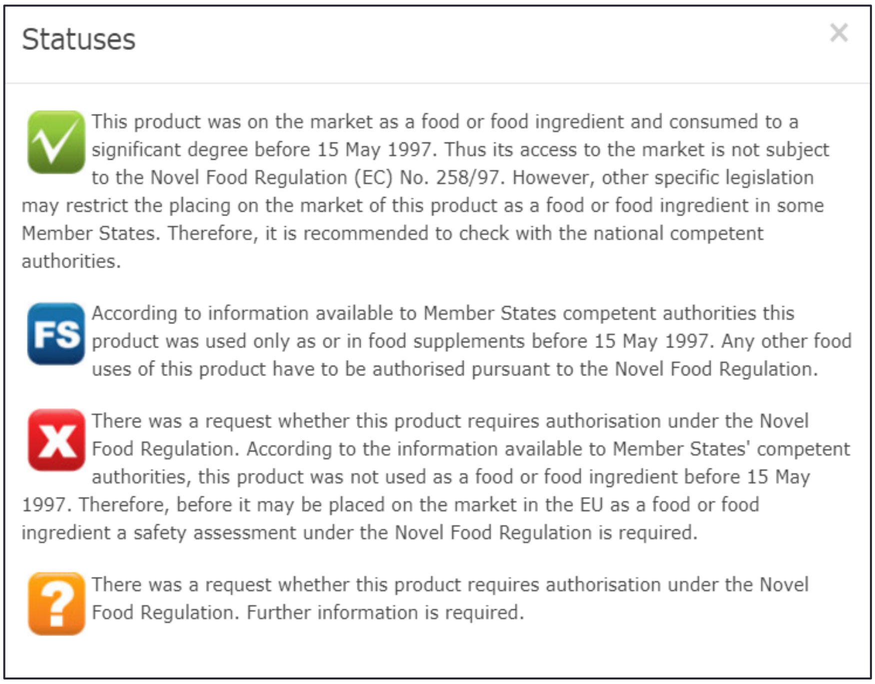
I - LIST OF EDIBLE SPECIES

I.1. Review of existing documentation in the EU/novel species

The European Union has an online "Novel Food Catalogue" in which users can search for all types of food. It lists products of animal and plant origin and other substances subject to the Novel Food Regulation, based on information provided by the EU Member States. It is a non-exhaustive list and serves as orientation on whether a product will need authorisation under the Novel Food Regulation. A Novel Food is defined as food that was not consumed to a significant degree by humans in an EU country before 15 May 1997 when the first Regulation on new food came into force.

Users looking for a particular seaweed species may or may not find the species in question in the Novel Food Catalogue (2018). All seaweed species currently listed have the status of “non-novel food”/green tick (Figure 21), indicating that they are accepted as food, as their use in Europe before 15 May 1997 has been proven, and they are therefore not subject to Regulation (EC) No 258/97 on novel foods. Note that the “Statuses” text box needs to be updated, since the present Novel Food Regulation - called “Regulation (EU) 2015/2283” - repeals and replaces the former Regulation (EC) No 258/97, which is cited elsewhere on the European Commission’s websites.

If a seaweed species is not listed, it means either that no request has been made for its authorisation as food by Regulation (EC) No 258/97 on novel foods (or 2015/2283 as mentioned above), or that it was already accepted as food before 15 May 1997. Seaweeds in the latter case include several species of *Porphyra* and *Ulva* sp. (Table 7).



Statuses

✓ This product was on the market as a food or food ingredient and consumed to a significant degree before 15 May 1997. Thus its access to the market is not subject to the Novel Food Regulation (EC) No. 258/97. However, other specific legislation may restrict the placing on the market of this product as a food or food ingredient in some Member States. Therefore, it is recommended to check with the national competent authorities.

FS According to information available to Member States competent authorities this product was used only as or in food supplements before 15 May 1997. Any other food uses of this product have to be authorised pursuant to the Novel Food Regulation.

X There was a request whether this product requires authorisation under the Novel Food Regulation. According to the information available to Member States' competent authorities, this product was not used as a food or food ingredient before 15 May 1997. Therefore, before it may be placed on the market in the EU as a food or food ingredient a safety assessment under the Novel Food Regulation is required.

? There was a request whether this product requires authorisation under the Novel Food Regulation. Further information is required.

Fig. 21: Screen dump of the different categories of statuses for novel food applications towards approval as non-novel food (Novel Food Catalogue, 2018). Note that the present Regulation is (EU) 2015/2283, and not 258/97.

According to the online European Novel Food Catalogue, the below listed species (Table 7) are accepted for use as food (non-novel) and are not subject to Novel Food Regulation (EC) No. 258/97 (nor, consequently, the updated Regulation (EU) 2015/2283; Novel Food Catalogue, 2018). This is because these specific seaweed species have a history of significant consumption as a food or food ingredient before 15 May 1997 in the EU.

Table 7: Seaweed species (scientific and common names) categorised as: not accepted as food (due to no application for authorisation) or accepted as non-novel food in the EC catalogue of novel food (Novel Food Catalogue 2018), including comments for the list's improvement. Furthermore, species accepted as food before May 15, 1997, are listed as "accepted as food". Species listed are Atlantic species and/or on the food market in EU.

Scientific name	Common name	Accepted as food	EU Novel Food Catalogue	Comment
Brown seaweed				
Alaria esculenta	Winged kelp	YES	Non-novel food*	
Ascophyllum nodosum	Rockweed	YES	Non-novel food*	
Cladosiphon okamuranus	Mosuku	NO	Not accepted as food	Imported
Durvillaea antarctica	Cochayuyo	NO	Not accepted as food	Imported
Eisenia bicyclis	Arame	YES	Non-novel food*	Imported
Fucus evanescens	-	NO	Not accepted as food	
Fucus serratus	Toothed wrack	YES	Non-novel food*	
Fucus spiralis	Spiral wrack	YES	Non-novel food*	
Fucus vesiculosus	Bladderwrack	YES	Non-novel food*	
Himanthalia elongata	Sea spaghetti	YES	Non-novel food*	
Laminaria digitata	Oarweed	YES	Non-novel food*	
Laminaria hyperborea	Tangle	NO	Not accepted as food	
Laminaria longicruris	-	YES	Non-novel food*	

Laminaria ochroleuca	Golden kelp	NO	Not accepted as food	Historical data exist; needs to go through authorization
Lithothamnium calcareum	Mäerl	YES	Non-novel food*	
Saccharina japonica		YES	Non-novel food*	Imported, former *Laminaria japonica*
Saccharina latissima	Sugar kelp	YES	Non-novel food*	
Sargassum fusiforme	Hizikia/Hijik	YES	Non-novel food*	*Called Hizikia fusiforme* in list
Undaria pinnatifida	Wakame	YES	Non-novel food*	Imported. Exotic species in Europe (farmed in France, wild harvest elsewhere)
Red seaweed				
Chondrus crispus	Irish Moss	YES	Non-novel food*	
Gracilaria gracilis/verrucosa	Thin dragon beard plant	YES	Non-novel food*	Should include more species.
Grateloupia turuturu		NO	Not accepted as food	Exotic species in Europe. Widely consumed as food in Asia.
Osmundea pinnatifida	Pepper dulse	NO	Not accepted as food	Historical data exist; needs to go through authorization
Pyropia tenera	Nori	YES	Non-novel food*	Pyropia species were previously named Porphyra
Porphyra laciniata,		YES	Accepted as food**	
Porphyra umbilicalis		YES	Accepted as food**	
Pyropia yezoensis		YES	Accepted as food**	
Pyropia leucosticta		YES	Accepted as food**	
Porphyra dioica		YES	Accepted as food**	
Porphyra purpurea		YES	Accepted as food**	
Palmaria palmata	Dulse	YES	Non-novel food*	
Vertebrata lanosa (former: Polysiphonia lanosa)	Seaweed truffle	NO	Not accepted as food	

Green seaweed				
Enteromorpha sp.	Aonori or green laver	YES	Non-novel food*	This is the same species as (morphologically different from) the sea lettuce
Caulerpa lentillifera	Sea grapes/green caviar	NO	Not accepted as food	Imported in Europe for human consumption.
Codium tomentosum	Dead man's finger	NO	Not accepted as food	Historical data exist; needs to go through authorization. Should also consider the exotic species C. fragile (if harvested).
Ulva lactuca	Sea lettuce	YES	Non-novel food*	Should include more species
Ulva sp.	Sea lettuce	YES	Accepted as food**	

**These non-novel foods are species accepted as foods because of their presence on the market before 15 May 1997. Checking with competent authorities is recommended (see Figure 21).*
***Already accepted as food in France since 1990 (before 15 May 1997; Hélène Marfaing, CEVA, personal communication, 2018; AFSSA 2009), these species of seaweed are authorised for food consumption. France was the first European country to establish a specific regulation concerning the use of seaweeds for human consumption as non–traditional food substances.*

The species that companies want to market and that are not accepted as food or "non-novel food" must undergo the authorisation process through Regulation 2015/2283, most likely with help from national authorities. However, documentation on significant use of the species as a food or food ingredient in Europe before 15 May 1997 can also help the seaweed species shift from the bottom category of Figure 21, then move up in category through the process, and finally be accepted as food (see more below). Acceptable documentation showing the consumption of food/seaweed before the given date 15 May 1997 includes invoices, import documents, price lists, national statistical data, dated labels or packaging materials, recipes mentioning the ingredients, or other relevant material. If no documentation exists, the authorisation may be given and the seaweed authorised as "novel food".

The EU list of novel food approved since 1997 can be found in the Commission Implementation Regulation (2017; this includes approvals given through the simplified "substantial equivalence" procedure under the former regulation 258/97). Some European countries such as Germany, Belgium and Italy may have their national lists on the use of food and food ingredients. The information in these lists is not necessarily fully accepted by all European countries, and, therefore, not necessarily incorporated in the Novel Food Catalogue. In addition, some authorised novel foods are found on a list among downloadable documents and do not come up from an online search in the Novel Food Catalogue.

Only one species of *Ulva* is listed in the Novel Food Catalogue, but *Ulva sp*. were already accepted as a food before the catalogue's compilation. Therefore, they are not included in the list. This also applies to most *Porphyra* species, and only *P. tenera* appears on this list of non-novel foods (Hélène Marfaing, CEVA, personal communication, 2018). However, species such as *Codium fragile, Osmundea pinnatifida, Caulerpa lentillifera* and *Vertebrata lanosa* are marketed even though they are not on the list of "accepted as food". Therefore, it is appropriate to recommend that already marketed species should be documented of use before May 15, 1997, and recognized as non-novel food, or to be authorised by the Novel Food Regulations and get the status as novel food.

Species such as *Codium fragile, Osmundea pinnatifida, Caulerpa lentillifera* and *Vertebrata lanosa*, are marketed even if they are not accepted as food in EU.

It is recommended to update the list.

New compounds extracted from seaweeds (as well as from seaweed species authorized as food) should be checked for their eligibility as food ingredients, for example, according to the Commission Implementing Regulation (EU) 2017/2470 and undergo application for acceptance. Fucoidan extracts from the seaweeds *Fucus vesiculosus* and *Undaria pinnatifida* (described and specified in the food category with a maximum intake of 250 mg/day) are already accepted.

If a product does not comply with specifications (e.g. extraction method or solvent used), there is a need for an amendment/expansion of the existing specifications under the Novel Food Regulation. However, the demands for documentation will most likely be less weighty than for a full/new application. Questions regarding the data needed for a new product should be directed to the EFSA (European Food and Safety Authority; New Novel Food Application, 2018).

Species identification and product standardisation are key elements for market development.

II.2. Species identification

In order to check which seaweed is marketed and consumed, it is necessary to identify the species being cultivated and harvested. Species can be identified by visual inspection (morphology, possibly including microscopy) by a qualified phycologist, or by more advanced methods such as sequencing genomic DNA or RNA, especially when morphology is in doubt. There are currently no standards on the identification procedure. However, a technical committee established recently (in 2017, under EU mandate) has identified this as one of the important priorities for algal standardisation (CEN/TC 454 - Algae and Algae Products). Within four years, recommendations will be addressed to the European Commission on the procedures used on the market. In the future, legislation may set standard procedures.

II.3. How to deal with imported goods and species?

The main seaweed species imported into Europe are wakame (*Undaria pinnatifida*), nori (*Porphyra* and *Pyropia* sp.), arame (*Eisenia bicyclis*) and hijiki (*Sargassum/Hijiki fusiform*), all of which are accepted as food, but not the *Caulerpa* species. Imported seaweed is subject to national legislation, and companies follow common food legislation on hygiene, labelling, food safety etc. The importer must specifically register import activities (Helle Eriksen, Danish Food Authority (personal communication, 2018).

A few years ago, in Denmark, food control by random analysis recorded excessive levels of inorganic arsenic in some hijiki seaweed imported from Asia, and sold in Danish healthcare stores, and this lot was withdrawn. More recently (summer 2018), national authorities withdrew seaweeds from the market in Germany and Belgium, due to high iodine content, but the Danish authorities did not act upon this alert. This is because Danish risk-assessment experts, particularly familiar with seaweed, judged that the concentration did not justify concern (Max Hansen, The National Food Institute (DTU Food; personal communication, 2018).

II - QUALITY PATTERNS

Another obstacle is the "handleability" of seaweeds for the food-distribution chain and the lack of best practices for well-developed and adapted conservation and preservation methods (standard industrial classification codes). Conventional freezing has not proved to be the best option; fresh transport is a challenging task, due to the rapid degradability of the product (in particular the visual aspect, which is an important selling factor); and drying has proved very expensive, mainly due to the high-water content and physical properties of many seaweed species.

Food preservation needs to maintain nutritional quality, organoleptic properties, and food safety.

II.1. Post-harvest treatments and product shelf-life

The water content of macroalgae is high (70 to 90%) although variable among species. Consequently, macroalgal biomass is generally characterised by rapid microbial decomposition once harvested (Enríquez et al. 1993). Therefore, appropriate preservation methods are required to maintain biomass quality and ensure product safety. In the case of using seaweeds in food applications, maintaining the nutrient content and enhancing organoleptic properties (flavour, colour, and texture) as well as minimising potential food-safety issues, are of high priority. Food-preservation techniques such as drying and freezing are commonly used to stabilise seaweed biomass but may also affect the characteristics of the raw material and its content in nutritional compounds, depending on the species. Alternative post-harvest treatments to increase shelf-life of fresh seaweeds include short-term storage in seawater (Stévant et al. 2017b) and cold storage (Liot et al. 1993).

Therefore, it is recommended that industry classification codes be developed that highlight best practices in processing and storage. This could be developed through interdisciplinary collaboration between research institutes, companies, and authorities across Europe. Below is some of the current knowledge on quality parameters and safety issues. The quality parameters for seaweed stability and food safety are a combination of:

i) water activity, which reveals whether the biomass includes water, a high level of which could allow microbial growth even if the biomass has been dried;

- *ii)* microbial studies and shelf-life and storage time;
- *iii)* stability concerning nutritional value;
- *iv)* the effect of different treatments;
- *v)* the concentration of contaminants and harmful compounds;
- *vi)* the bioavailability of nutritional compounds and harmful substances.

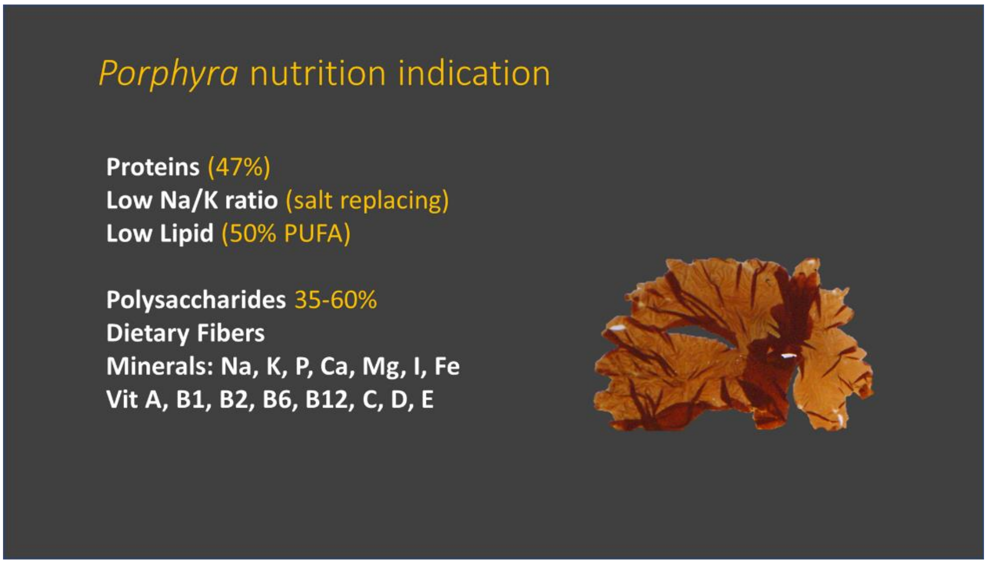
However, in contrast with the rapid development of seaweed-cultivation technology, knowledge remains limited regarding the effects of preservation treatments on the biomass quality of species of commercial interest in Europe, e.g. *Saccharina latissima*, *Alaria esculenta* and *Palmaria palmata*. It is one of the main factors currently limiting product development (Skjermo et al. 2014; Stévant et al. 2017c). Seaweeds do not react the same way as conventional vegetables (e.g. Wells et al. 2017). Best storage procedures must be determined for each species and products, along with the establishment of best practices for product shelf-life evaluation. Understanding the behaviour of seaweed biomaterial is a key to developing processing strategies that will maximise the quality of the products to be used as food and food/feed ingredients and as a raw material for the provision of valuable compounds.

II.2. Nutritional values

II.2.1 VARIABLE NUTRITIONAL VALUE BETWEEN SPECIES

Seaweeds are known for their high nutritional, nutraceutical and bioactive properties (Holdt & Kraan 2011; Stengel et al. 2011). Yet being very diverse, their nutritional composition varies by species, geography, environment, and season, and even within populations.

The protein content of seaweeds is generally low, making up 5-15% of the dry weight, but for some red algae such as *Palmaria* and *Porphyra* it can reach up to 47% of DW (Figure 22). Polysaccharides can be used as dietary fibres, for bioactive properties, or due to their functional properties as commercial stabilising agents (agar, alginate and carrageenan) and generally make up 35-60% of DW. They are generally not digestible and do not count as calories. Similarly, the energy provided by lipids is low, due to their low content (maximum 4% of DW). However, the proportion of PUFA's (Poly Unsaturated Fatty Acids) incl. omega-3 fatty acids is high, representing up to 50% of lipids (Holdt & Kraan 2011; Marinho et al. 2015).



Porphyra nutrition indication

Proteins (47%)
Low Na/K ratio (salt replacing)
Low Lipid (50% PUFA)

Polysaccharides 35-60%
Dietary Fibers
Minerals: Na, K, P, Ca, Mg, I, Fe
Vit A, B1, B2, B6, B12, C, D, E

Fig. 22: Porphyra *nutritional facts.*
(Design: Michèle Barbier, Institute for Science & Ethics)

2.1.1 Minerals and vitamins

Seaweeds are rich in minerals such as Na, K, P, Ca, Mg, I, and Fe. Seaweeds have 10-20 times the amount of minerals usually found in land plants, due to the minerals concentrated in seawater (Gupta & Abu-Ghannam 2011; Makkar et al. 2016). Their relatively low Na/K ratios make seaweed an attractive salt-substitute ingredient in the food industry, resulting in healthier mineral profiles in manufactured-food products (Rioux et al. 2017). Vitamins in seaweed generally include A, B_1, B_2, B_6, B_{12}, C, D and E. Vitamins and minerals can reach up to 10-100 times higher concentrations than fruits and vegetables on a dry-weight basis.

2.1.2 Iodine

Iodine (I) is essential and used in the thyroid gland for metabolic management. Some studies have also shown bioactive effects on breast cancer, and in fibrocystic breast disease (Brown et al. 2014). Iodine is highly concentrated in some of the large brown seaweeds such as sugar kelp (*Saccharina latissima*) and bladderwrack (*Fucus vesiculosus*; up to 8,000 ppm). This results in iodine as the limiting factor for the recommended daily intake of seaweed (Holdt & Kraan 2011; Marinho et al. manuscript in preparation; Stengel et al. 2011). And World health organisation WHO has suggested seaweeds as a healthy alternative to salt iodisation, to improve the iodine status of populations deficient in iodione. It is important to bear in mind that Europe is the continent with the biggest population deficient in iodine (Andersson et al. 2007).

However, the iodine level in sugar kelp can be greatly reduced by a simple soaking treatment in heated fresh water (Lüning & Mortensen 2015; Stévant et al. 2017a) although this will also reduce the concentration of vitamins and soluble compounds (e.g. minerals, mannitol). Not much is known regarding the speciation of iodine/chemical form (inorganic iodine forms (iodide and iodate) and organo-iodine forms (MIT, DIT and possible others) found in seaweeds (due to a lack of identification methods), nor on their bioaccessibility/uptake in the human or animal digestive tract. See more on iodine and legislation and health risks in seaweeds below.

Iodine is highly concentrated in some brown seaweeds and can be a limiting factor for the recommended daily intake of seaweed.

Its level can be reduced by soaking in heated freshwater.

2.1.3 AS A FEED INGREDIENT

Some seaweeds (especially the brown) are a rich source of natural antioxidants such as polyphenols (Farvin & Jacobsen, 2013), antimicrobial activities (Vatsos & Rebours 2014), and polysaccharides which have demonstrated various bioactive properties (Holdt & Kraan, 2011). Also, the pigment fucoxanthin (Fung et al. 2013) in brown species offer multiple applications in human and animal nutrition, and health and welfare (Figure 23).

Seaweeds had seen a renewed interest as feed ingredients since the 1960s when kelp-based seaweed meal was produced in Norway. Seaweed can be a valuable alternative or supplement to livestock feed, especially as a source of valuable nutrients, complex carbohydrates, pigments and polyunsaturated fatty acids. Vegetable and cereal proteins are frequently used in the manufacture of food products for animals, fish and humans, but they often lack essential amino acids or an adequate/balanced profile to match the necessary amino acids and/or proteins (Marinho et al. 2015). However, several seaweeds investigated so far have proved to contain high protein fractions with potential use in the feed. Other nutritional and/or bioactive benefits have also been identified from the use of seaweed in feed for example for cows, fish, chicken, leading to a wide range of effects such as increased biomass, milk production, the colour of flesh (Holdt & Kraan, 2011). Some companies already list seaweed as a feed supplement in their product portfolios, but for all available seaweeds there are still knowledge gaps to be filled before seaweed can be fully exploited as replacements for today's conventional feed raw materials such as soy products.

The methods for determining the different nutritional properties of seaweeds (total lipids and fatty acids, proteins and amino acids, pigments) are to be recommended as standards by working groups of CEN/TC 454 Algae and Algae Products.

II.2.2 ORGANOLEPTIC PROPERTIES

Seaweed morphology is an important feature to take into consideration. Homogeneity of shape, length and thickness are especially important if the mechanisation of seaweed harvest and processing operations is to be developed, or if the Asian market - particularly stringent on this aspect - is targeted. Stipe thickness may also influence the kind of food product that can be developed, i.e. thin kelp blades are ideal for kelp chips whereas thicker blades bring a crunchy texture to kelp salad.
In addition to their nutritional benefits, seaweeds, including common species along the coast of Europe, have both flavour-enhancing and physico-chemical properties (texture, water- and fat-binding properties, colour) that can be applied to the field of gastronomy and the food industry (Hotchkiss 2009). An Irish report describes the taste of common seaweed, its ability to replace salt and its supply of flavour (in particular sodium; Hotchkiss 2010), and its resulting use as an ingredient in common commercial products.

However, it is recommended that "seaweed flavour words" be developed to describe the nuanced flavours of seaweed and their evolution, so that seaweed flavour is not only summed up as "the aroma of the sea". Indeed, comparing the different seaweed species to one another is like comparing bananas and broccoli. Recent studies highlight the variety of flavour profiles among seaweed species e.g. the distinctive umami character of dulse (*P. palmata*) (Mouritsen et al. 2012; Chapman et al. 2015) and Japanese kombu (*Saccharina japonica*), the green-tea aroma and flavour of sugar kelp (*S. latissima*; Stévant et al. 2018).

Seaweed's organoleptic characteristics can either be boosted or reduced by processing and storage, depending on the species and the treatment employed.

SEAWEED HAS NUANCED FLAVOURS THAT AWAIT DISCOVERY IN EUROPE

After harvest, Japanese kombu is generally dried and stored for several years to develop characteristic aromas (like a grand cru), suggesting that some sensory properties can be specifically produced using appropriate processing and storage conditions. Although the inclusion of seaweed in the diet is considered an exotic practice among Western populations and is largely associated with Asian culinary traditions, sensory-assessment groups are being established in Western European countries and Canada to support the development of seaweed-based food products from local species. Increased knowledge in this field of research will help to make seaweed more attractive to Western palates.

In Canada, the first sensory panel for seaweed food products was set up in 2016 at Merinov. A sensorial training pack was developed for the experts of the panel. The National Food Institute, Technical University of Denmark (DTU Food), but also AlgaPLus (Portugal), Matís (Iceland) and Møreforsking AS (Norway) have well-trained sensory panels, focusing on marine products in particular. Matís has developed sensory methods for seaweed and performed a sensory evaluation of seaweed in some different projects since 2012. It includes Generic Descriptive Analysis to evaluate how different factors including maturation may affect sensory characteristics.

III - SOURCES OF POTENTIAL CONTAMINATION

III.1. Microbiological contamination

A Danish report has reviewed knowledge on microbiology and safety regarding seaweed consumption and concluded that while very little was known and studied, there was no reason to be concerned (Hendriksen & Lundsteen 2014). The Danish Food Authorities (Danish Food Authorities 2018) recently conducted a study on six species of seaweed from coastal samples taken at 65 locations in Denmark. The existence of *E. coli* and *Salmonella* was tested on freshly harvested seaweed. The conclusion was that, based on these results, there were no geographical areas where it was not safe to harvest seaweed. It was further concluded that there was no danger in harvesting algae in Danish coastal areas if they were not harvested in the immediate vicinity, for example, of a sewage disposal point and ports.
Nevertheless, this does not exclude the possibility of microbial contamination of seaweeds during IMTA cultivation and drying processes.

A recent Japanese study describes serial food-poisoning outbreaks caused by norovirus, traced in contaminated shredded dried laver seaweed that was provided for school lunches (Somura et al. 2017). It should be noted, however, that unlike filtering species like bivalves, seaweed species do not concentrate bacteria and viruses, and the challenges should hence be much smaller than for bivalves. A recent study on sugar kelp and mussels at heavily contaminated locations showed that while mussels contained up to 170 CFU/g (17,000 MPN/100 g), no *E. coli* were detected in the kelp (<10 CFU/g). This suggests that requirements for *E. coli* analyses in future EU ecological seaweed regulations are unnecessary (Arne Duinker, Institute of Marine Research, Norway, personal communication, 2018).

In general, industry classification codes are lacking for washing, drying, storage or shelf-life. As the authorities do not have the necessary expertise, they should encourage experts to draft codes of best practice for industry classification that they can then evaluate. Some EU countries have initiated this process, but it is recommended that a joint international system is deployed for interdisciplinary cooperation between researchers, companies and authorities from all countries.

III.2. Heavy metals, chemicals and other molecules of concerns

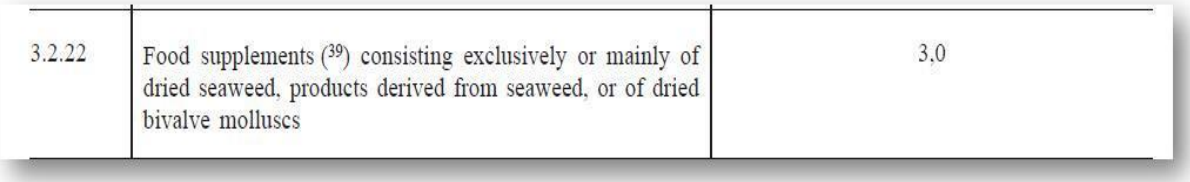
III.2.1 LEGISLATION

Seaweeds are extremely good at accumulating minerals, metals, and also, unfortunately, heavy metals if these are present in the surrounding environment. The latter include mercury, cadmium, and lead (Table 8). EU legislation exists on the allowed threshold values of some heavy metals in seaweed used as supplements (Commission Regulation 1881/2006). The limits set by France are only recommendations (AFSSA 2009), whereas the US threshold values are set by legislation on food, and European legislation concerns food supplements only (Holdt & Kraan 2011; Commission regulation 1881/2006). It is interesting to note the large disparity in iodine threshold values, with max. 2,000 ppm recommended in France and max. 5,000 ppm in the US legislation.

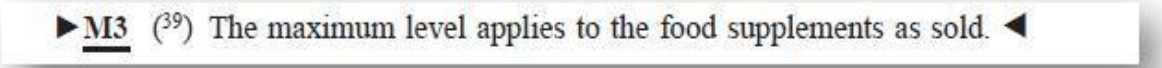
Table 8. Quality criteria applied to edible seaweed sold in France (AFSSA recommendations 2009), regulations in the USA, and dietary supplements in EU (the latter concentration is based on weight "as sold", most likely to be dry weight; Holdt & Kraan, 2011; COMMISSION REGULATION (EC) No 1881/2006, 2006).

Limit (mg kg^{-1} DM, ppm)			
Compound	**France**	**EU**	**USA**
Lead	<5.0	<3.0	<10.0
Cadmium	<0.5	<3.0	
Mercury	<0.1	<0.1	
Inorganic arsenic	<3.0	No regulation	<3.0
Iodine	<2,000	No regulation	<5,000

The threshold levels described in the Contaminants in Foodstuffs (COMMISSION REGULATION (EC) No 1881/2006, 2006) regulation (only for seaweed as a food supplement) should always specify if the concentrations are based on dry or wet biomass/food, as in the example of Cadmium (Cd):



3.2.22	Food supplements (39) consisting exclusively or mainly of dried seaweed, products derived from seaweed, or of dried bivalve molluscs	3,0



►**M3** (39) The maximum level applies to the food supplements as sold. ◄

Note 39 indicates that the threshold levels in food supplements apply to the product “as sold”- which could either be in dry or wet weight depending on the product. However, as “dried” is mentioned several times, it is “expected” - though not clearly stated - that the threshold applies on a dry-weight basis (COMMISSION REGULATION (EC) No 1881/2006, 2006).

Indications are required on whether calculations of the specific threshold values for Cd, Pb, Hg, iAs, and I in seaweeds are based on FW or DW.

The European Commission EFSA (European Food Safety Authority) working group for industrial contaminants is looking at updating this legislation on contaminants and would like to include seaweed as food (working document on contaminants in seaweed, unpublished; Commission recommendation 2018). As part of this project, DTU Food will host an EFSA fellow for ten months during 2018/19 to perform mineral, heavy-metal, iodine and inorganic-arsenic analyses and make a risk-benefit assessment. These results will be included in the EFSA working-group considerations.

The recommendation on monitoring contaminants including metals is a great advance in the seaweed market in Europe, promising to clear rumours and settle issues if and when they arise about heavy metals and seaweed, rather than relying on national interpretations on seaweed as food or the EU’s regulations on seaweed as food supplements. For example, in Commission recommendation (2018) *Codium* sp. is mentioned as a seaweed species for the monitoring of contaminants. However, these species are listed neither in the Novel Food Catalogue (novel or non-novel), nor in the non-official list of seaweeds recognised as food before 15 May 1997 provided by CEVA, France (see Table 7). Therefore, it seems that one body of the EU has accepted the species as food while the Novel Food Catalogue/EU food authorisation has not.

Seaweeds for feed are regulated by threshold limits for lead, cadmium and mercury (Table 9). The market barrier is the limit for total arsenic. However, feed legislation should also be updated because both natural populations and cultivated *S. latissima* quite often exceed this authorised arsenic concentration based on total arsenic. An update is thus recommended to change the limit for total arsenic to a threshold value based solely on the hazardous inorganic arsenic instead.

Table 9. Legislation on heavy metals and total arsenic in the feed (EU Commission Regulation 2015; OJEU Directive 2002).

Toxic minerals	**Limit (mg kg^{-1} DM, ppm)**
Lead	<10
Cadmium	<1
Mercury	<0.1
Total arsenic	40

III.2.2 KAINIC ACID

Among the chemicals of concern is the neurotoxin kainic acid, found in a few different seaweeds like *Digenea simplex* and *Palmaria palmata* (in some found strains of *P. palmata*, high concentrations are cause for concern). However, in *P. palmata* only large consumption volumes (30 kg dry seaweed per day) can raise a risk (Mouritsen et al. 2013).

III.2.3. PROSTAGLANDIN

In Japan, consumption of fresh *Gracilaria vermiculophylla* (“Ogonori”) - for example, as a main constituent of salad - has occasionally caused severe cases of prostaglandin intoxication, in particular when the seaweed was consumed together with fish. The alga contains an enzyme, cyclooxygenase, that can transform - after ingestion of arachidonic acid, a polyunsaturated fatty acid particularly abundant in fish - into prostaglandin. However, cooking the seaweed reliably inactivates the enzyme (Noguchi et al. 1994).

III.2.4 ARSENIC

Sargassum spp., including commercial hijiki, contain a significant amount of inorganic arsenic. Normally and generally, organisms absorb inorganic arsenic (relatively high in marine waters) and incorporate it, for example, into arseno-sugars, making arsenic safe. However, *Sargassum* spp. absorb higher concentrations and accumulate them as inorganic arsenic (up to 88 ppm compared to only 0.34 ppm in *Fucus vesiculosus*), which, when accumulated in the human body, are carcinogenic (Holdt & Kraan 2011). The quality criteria applied to edible seaweed sold in France, the USA and for dietary supplements in the EU, are different (Holdt & Kraan 2011): in the United States, legislation requires a level below 3 ppm; in the EU, there is no threshold limit.

Under feed legislation, the threshold concentration is regulated on the basis of total arsenic (i.e. both organic and inorganic), at 40 ppm (Table 9). However, organic arsenic is not considered harmful. Legislation has not kept pace with technological advances in the development of methodologies, which now makes it possible to distinguish between inorganic and organic arsenic. However, several seaweeds, such as sugar kelp cannot comply with the present threshold concentration, thus limiting the market for seaweed for feed. An update on legislation on feed, as on seaweed for food, is, therefore, recommended.

III.2.5 CADMIUM

Recent studies reported the ability of *Alaria esculenta* to accumulate cadmium over the threshold value of 0.5 mg kg^{-1} DW recommended by France (Table 8; Mæhre et al. 2014; Stévant et al. 2017a; Biancarosa et al. 2018). Cadmium intake following daily consumption of 3.3 g dried seaweed (estimated as the average Japanese seaweed consumption) was calculated based on the maximum values measured in *A. esculenta* samples and compared to tolerable intake levels established by international authorities (Stévant et al. 2017a). Based on the results, the cadmium level in *A. esculenta* did not pose a threat to the consumer, whereas a similar consumption pattern for *S. latissima* resulted in an iodine intake largely exceeding the nutritional recommendations for this element.

III.2.6 DIOXIN

Dioxin is found in different chemical forms such as Polychlorinated Dibenzo-P-Dioxins (PCDD), and is accumulated in the food web, especially in fat tissues. For example, it is found in high concentrations in the fat of the carnivorous Baltic fish salmon (Niemirycz et al. 2017).
An acceptable limit of dioxins in seaweed has not been established so far. However, the EU Commission agreed on maximum levels (ML) and action levels for dioxins and dioxin-like PCBs in human food and feed in December 2005. Furthermore, new combined maximum dioxin and dioxin-like PCB levels in seafood for human consumption set new maximum levels that applied from 4 November 2006 (EU Commission Regulation 199/2006).

New MLs have been set for dioxin (8 pg g^{-1}) furans (4 pg g^{-1}) and dioxin-like PCBs (polychlorinated biphenyls, 4 pg g^{-1}), while other values are given for marine oils, including fish and liver oil (respectively 10, 2, and 8 pg g^{-1}) and eel (12, 4 and 8 pg g^{-1}). In plants for food, there are no MLs for dioxins, but there is an ML for fruits and vegetables. A product may be marketed even if it exceeds the action limit, but the authorities are then required to monitor the sources. Plants do not concentrate dioxins in the food web the way that fish do for example. In most cases, dioxin is not absorbed by the plant, but it may be adsorbed in particulate form. This means that the concentration of dioxins in plants is generally low compared to foods high in animal fats or fatty fish from contaminated areas (Tommy Licht Cederberg, Senior Advisor in Food Analytical Chemistry, DTU Food, personal communication, 2018).

A study on Japanese seaweeds *Undaria pinnatifida, Eisenia bicyclus, Sargassum fulvellum,* and *Ceramium boydenii* showed that the different isomers of PCDD (with the tetraCDDs as the most toxic) added up to concentrations of respectively 4.5, 28, 41 and 30 pg g^{-1} dry weight. The same study indicates that the PCDDs in seaweed come from combustion sources, such as municipal incinerators or power plants. PCDDs of natural origin, if any, were not determined due to the elevated concentrations coming from the mentioned combustion sources (Hashimoto & Morita 1995). No study has been published on dioxin concentrations in European seaweed, to the knowledge of this study's authors.

III.2.7 IODINE

Health risks associated with eating seaweeds depends on the products' content of potentially toxic elements, the quantity ingested over time, and the compounds' bioavailability in the human body. Based on a study of the consumption of edible seaweeds in France, the daily eating of 3.3 g (DW) seaweed valid for Japanese consumers appears rather unrealistic while a consumption pattern based on one to two meals weekly appears a more plausible scenario. However, if seaweeds excessively rich in iodine (and/or other potentially toxic elements, Table 8) are included in staple foods that are likely to be consumed daily (e.g. bread), doses should be considered so that the daily recommended upper intake of iodine is not exceeded (Arne Duinker, Institute of Marine Research, Norway, personal communication, 2018).

The German Federal Agency for Risk Assessment recommends a maximum concentration of 20 mg kg^{-1} of iodine in dried seaweed for consumption and a maximal daily uptake of 500 µg I d^{-1}.

The National Food Institute of the Danish Technical University (DTU Food) does not consider it a health problem if the upper limit (UL) of iodine intake exceeds that of adults (UL 600 µg I d^{-1}). Nor does it consider a problem if the upper limit for a meal is occasionally exceeded i.e. a very high iodine content in one intake is less harmful than a regular intake of a concentrated iodine food for several days. Excessive intakes of iodine over a prolonged period may result in thyroid complications in sensitive groups (e.g. I-deficient people, elderly, foetuses and neonates).
However, it is not possible to assess the health consequences for young children if the EFSA (2006) limit is exceeded (1-3 years; UL 600 µg I d^{-1}). Seaweed ingestion is unknown in most countries, so it is not possible to obtain an accurate estimate of iodine intake in Europe (including Denmark). The general approach of DTU Food is that seaweed can be part of a varied diet, but caution is recommended regarding the consumption of iodine (especially for children under 4 years of age) and some other seaweed compounds (Max Hansen, DTU Food, personal communication, 2018).

The development of appropriate regulations for edible seaweed and appropriate product labelling will ensure consumer safety and the sustainable development of a growing seaweed industry.

III.2.8 USE OF ADDITIVES, FERTILISERS, PESTICIDES

At the hatchery stage, it is very common practice to cultivate gametophytes, germlings and young sporophytes < 1 mm in tanks filled with enriched seawater (N, P, trace metals, vitamins). If the seaweed is to be certified "organic", this enrichment of nutrients in the hatchery/nursery phase should rely on "organic nutrients" or be by the Organic Seaweed reference (2007). Some organic standards (e.g. Canadian organic aquaculture standards) do tolerate this practice but prohibit the addition of artificial nutrients on marine farms. From a scientific perspective, there is no reason to prohibit careful fertilisation of a kelp farm in the open ocean (e.g. with a device that allows slow diffusion of N inside the farm) if there is a documented constant or seasonal nitrogen shortage issue on the farm or in the area. Of course, N addition should be undertaken carefully (at the farm scale, for short periods, at the right dosage), taking into consideration current intensity, kelp biomass and kelp-uptake rate etc., in such a way that there is no risk of water eutrophication on a large scale. Theoretically, N addition could also be performed by briefly soaking the seaweeds in a tank to let them soak up and store nitrogen in their tissue. This approach would however, in most Western countries, most likely raise much opposition from fishermen, coastal populations, environmentalists and shellfish farmers, fearing eutrophication that can lead to (toxic) algal blooms, among other concerns. It would therefore negatively affect the environmentally- friendly image of seaweed aquaculture and have a disastrous impact on its sales.

Pesticides may be taken up by seaweed if present in the surrounding environment. In the EU's Commodity List for which maximum residue limits (MRLs) are set for commodities used for food, algae are cited under the category "Algae and prokaryotic organisms" with mentions of some species like *C. crispus*, *S. japonica* and *Ascophyllum nodosum*. The MRL for pesticides is by default 0.01 mg kg^{-1} and applies to any pesticide even if it is not specifically mentioned (Regulation 396/2005).

IV - STANDARDISATION AND CERTIFICATION

IV.1. Standardisation

Hafting et al. (2015) write that Hazard Analysis Critical Control Points and ISO22000 safety protocols are being developed for the production of seaweeds, and adherence to these protocols will become mandatory.

The Technical Commission CEN/TC 454 Algae and Algae Products is, as mentioned, at present working on standardising methods and data sheets for food and feed use. This will lead to recommendations being made to the European Commission within the next four years.

The surveillance of potentially undesirable compounds in edible and commercialised seaweeds, along with further investigation of their behaviour in the human body and effects related to their consumption, are essential.

IV.2. Organic certification

In Europe, organic certification of cultivated and natural populations of seaweeds is described in Commission Regulation (EC) No 710/2009 of 5 August 2009 amending Regulation (EC) No 889/2008 which lays down detailed rules for the implementation of Council Regulation (EC) No 834/2007 for the organic production of aquatic animals and seaweed.

In 2012, the Canadian General Standards Board published the Standards for Organic Aquaculture with a chapter on seaweed and aquatic plant aquaculture (CAN/CGSB-32.312-2012). Meanwhile, Europe has developed organic certification using the "leaf" label, or the "flower" used for non-food (Figure 23). However, the regulation as mentioned above is interpreted in different ways in different countries. Furthermore, in order to comply with other already-established national organic certification and labelling, producers and/or harvesters may need to comply with even stricter regulations.

Fig. 23: European organic-certification labelling.

To give an example, in Norway, all providers of organic products are certified by Debio that can authorise the organic (Ø) label. To grant certification, Debio focuses on: an operation report sent before a visit to the site; compliance with the rules on organic aquaculture and labelling of organic aquaculture products; risk assessment regarding possible sources of pollution that can affect the seaweed products. Furthermore, the producer is expected to comply with regulations for food (this includes testing for the presence of *E. Coli* when the products will be used for human consumption), and the company should come up with a reasonable plan for sampling where additional relevant analyses are included. For one Norwegian company, it took half a year to obtain the certified organic approval, but this timeframe can vary from one company to another (Lill-Ann Gundersen, Norgesvel, personal communication, 2018).

In France, the National Institute of Origin and Quality (INAO) has interpreted the European regulation on organic farming seaweed (CE n°710/2009). Organic certification is not so hard to obtain if the area where the seaweed is harvested, is located in water bodies in a “good" or “very good" ecological state. The attributed state should depend on the Water Framework Directive and whether the area corresponds to good sanitary and chemical criteria (Reydet & Böhm 2011).

The technical data sheet of Reydet and Böhm (2018) provides more information on organic seaweed for seaweed gatherers and farmers who wish to certify their production as organic (European regulation CE 834/2007).

Problems arise when cultivation or harvesting do not occur in a "good zone”, or else one not characterised by sanitary criteria. Sanitary criteria are derived from a regulation concerning oysters and mussels, with attribution of qualification as "A" or "B" by microbiological criteria. This means that if seaweeds are collected from an area which is not qualified for oyster and mussel production, sanitary information is not available unless the seaweed producers submit a heavy application file to the competent authorities (Hélène Marfaing, CEVA, France, personal communication 2018).

Tools are being developed to find suitable locations. For example, on the interactive map of Brittany shown in Figure 24, click on each zone allows users to check the different analysed criteria and to understand why some areas are not in a good ecological state (which was the "declassified" parameter).

In Iceland, the Vottunarstofan Tún is the independent conformity assessment body for organic certified farming and processing. The guidelines can be found on Tun (2018), where organic seaweed certification falls under the category of “sustainable harnessing of natural resources” (Rósa Jónsdóttir, Matis, Iceland, personal communication, 2018).

Work is ongoing in Denmark to develop guidelines for industry on how seaweed producers (aquaculture or harvesting of natural populations) are to obtain “organic” certification. The first ones to be successfully certified Danish organic (Ø) were a cultivated-kelp producer and two companies harvesting natural populations of bladder wrack, but the processes took a long time (about two years) and involved a high degree of national interpretation regarding information that is ”good to know", but not always strictly "necessary to know".

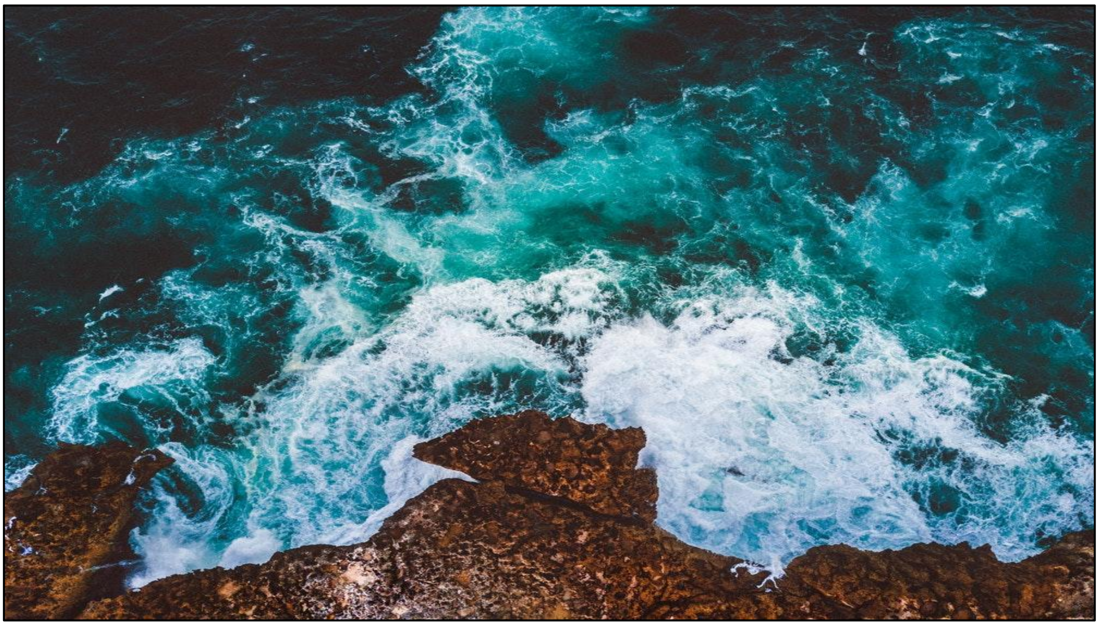


Photo credit: Ivan Brandura from Unsplash

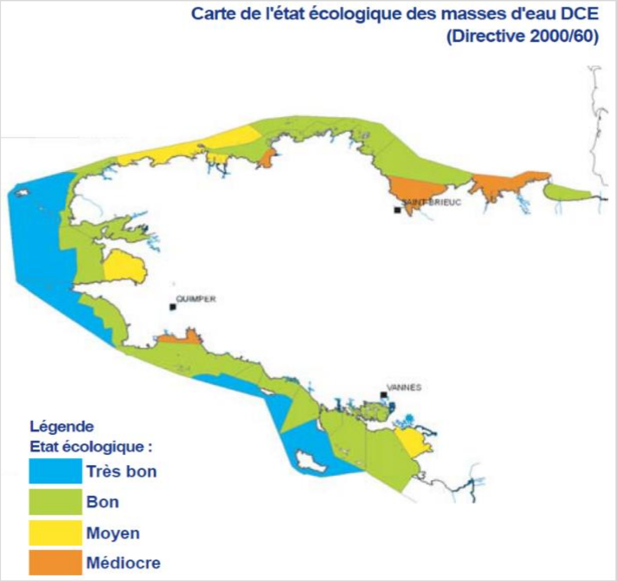


Fig. 24: Sample map showing waterbody states in Brittany, France. Colour codes indicate, for example a "good" or "very good" ecological state (Reydet & Bohm 2011). More details can be seen on the interactive map. Source: Map produced on February 9, 2011 by Manuelle Philippe based on data from the Loire Bretagne Water Agency on May 26, 2010.

In Germany, the organic-farming association Naturland has developed its own guidelines for the production of macroalgae from organic aquaculture that are stricter than the general EU guidelines. Naturland guidelines specify requirements for water quality (only waterbodies with "very good" or "good" quality according to the EU Water Framework Directive are considered acceptable), harvesting techniques (manual techniques are preferred, motorised techniques are only permitted if they can be shown not to have a negative impact on the marine ecosystem), the choice of ingredients during processing (generally more restrictive than EU guidelines) and social standards in Naturland farms. Naturland farms are also required to exclusively produce organic products.

V - RECOMMENDATIONS FOR FOOD SAFETY

NEW COMPOUNDS/FOOD INGREDIENTS

New compounds extracted from seaweed should be checked for eligibility, for example as food ingredients according to the Commission Implementing Regulation (EU) 2017/2470, or else undergo application for acceptance. So far, only the extracted compound fucoidan from the seaweed *F. vesiculosus* and *U. pinnatifida* (described and specified in the food category with a maximum intake of 250 mg d^{-1}) are accepted. If compounds have other specifications (e.g. on the described solvent for extraction), amendments can then be made for approval.

More scientific research to define the potential of seaweed as bioactive food is needed. At present, companies claim effects, but more research is needed to support these claims and feed the market. It is recommended that scientific proof leads to risk-benefit analyses on health, thereby taking pros and cons into consideration. For claims on seaweed as being nutraceuticals, bioactive foods, superfoods or even pharmaceuticals, more research and clinical proof is needed.

The identification of species is crucial to ensure that species are well identified when compounds are extracted for the market. It is essential that the ongoing work on standardisation of identification methodologies be supported and encouraged.

NOVEL FOOD LIST SPECIES

The European Commission Novel Food List should include species already on the market.
For the European Commission (online) Novel Food Catalogue, an overview should be made available, in order to avoid the confusion of authorized as food, novel and non-novel food species. To do so, it is recommended that:

- Only seaweeds that are in the process of becoming novel food or non-novel food should be listed in the Novel Food Catalogue.
- An official list of all seaweed species accepted as food before 15 May 1997 should be completed (possibly including notes on specific species accepted in different countries) to lighten the burden on stakeholders. **This list should include all seaweed species "accepted for food" list. Se below point.**
- If/when seaweeds are categorised as non-novel food (green tick off) they should be transferred to an "accepted for food" list (which also includes the species already accepted as food before 15 May 1997).

Seaweed species already on the market, but not yet listed, should go through the authorisation process for novel food; otherwise, they should not be on the market.

CONTAMINATION AND SEAWEEDS

Legislation on contaminants such as heavy metals and the troublesome iodine should be laid down for seaweed as food, and not just for seaweed as a food supplement, as is the present case. An EFSA (European Food Safety Authority) monitoring programme has been initiated, but this working group does not seem to be aligned with the EU body that works on the "Novel Food Catalogue".

Therefore, it is recommended that:

i) **Seaweeds should be recognised as "food", and not just a "food supplement" (an outdated approach) in the legislation of contaminants. This would align the legislation on contaminants and the Novel Food Catalogue.**

ii) **Heavy metals etc. in seaweeds should be monitored as their levels are highly relevant to the market. Such monitoring will contribute to removing market barriers and to producing clear signals/regulation on the threshold values of different contaminants.**

The EU working groups and bodies for the Novel Food Catalogue and the monitoring of heavy metals etc. should ensure that their work is linked and aligned. The seaweeds listed as being monitored for heavy metals etc. should be aligned with the list of novel and non-novel foods, and seaweeds accepted as food before 15 May 1997.

Legislation on the use of seaweed for feed needs to be updated. Only inorganic arsenic should be the focus of the threshold level and not the outdated total arsenic. Under the present feed legislation, the threshold level (40 ppm) is based on total arsenic (both organic and inorganic). However, it is now technically possible to distinguish the harmful inorganic arsenic from the organic arsenic that is not of particular concern.

Threshold values should be specified as being on a preferably dry weight (DW) (or wet weight, WW) basis. This must be clearly stated in the new legislation of contaminants in seaweed for food, and also in the legislation relative to seaweed for feed.

Risk-benefit analyses, including risk assessments, are necessary to assess advantages and disadvantages for health, such as high levels of iodine, heavy metals, nutrients or even nutraceuticals in algae, for the achievement of food safety. There is a need for general risk-benefit analyses of seaweed with clear guidelines on which element under which form is toxic and at what levels (daily or monthly intake?) and what chemical form is present in the seaweed. The initiated EFSA work on monitoring seaweeds is timely. The high concentrations of iodine accumulated in some large brown seaweeds are market barriers. More knowledge is recommended on speciation/chemical form and bioaccessability/uptake of seaweed iodine, and how to reduce iodine. New methods for detection of the different chemical forms are needed.

NATIONAL CONCERNS

Organic certification of cultivated and natural populations of seaweed has developed, but many different bodies and various processes exist for organic certification in the different European countries. It is most likely not possible to set up one organic certificate with aligned regulation regarding the organic label across Europe. Indeed, organic certification extends across all foodstuffs and beyond seaweed and has been implemented for decades, giving rise to differences between countries. However, best practices or minimum requirements could be shared.

Sensory-evaluation panels could be implemented at the national/regional level. It is recommended that vocabulary be created to describe the flavour of seaweed in order for the public to gain a better understanding of what they are buying, and what different seaweed can add to their food, as a spice, taste enhancer, supplement.

PRESERVATION

There is a need for increased knowledge about the impacts of post-harvest handling (e.g. preservation treatments) on the quality and stability of seaweed (e.g. nutrient content, organoleptic properties) to be used in food (food safety). Currently, no specific legislation exists relating to quality stability (e.g. is it still safe to eat seaweeds stored for two months?). It might be **advisable to check seaweeds for the presence of bacterial contaminants when stored for a few months (dryness, water activity). General studies are needed on red, green and brown algae to assess the long-term effect of drying.**

With the rapid development of seaweed-culture technology, knowledge about the effects of conservation treatments on the biomass quality of commercially important species in Europe, such as *Saccharina latissima, Alaria esculenta* and *Palmaria palmata*, remains limited. This is one of the main factors currently limiting product development. **The standardised methods for determining the different nutritional properties of algae (total lipids and fatty acids, proteins and amino acids, pigments) should be recommended by CEN TC 454 Algae and Algae Products.**

It is recommended that industrial classification codes/best practices for the preservation/ downstream processing of seaweeds be drafted by seaweed experts and transferred to the authorities. These codes could also be established in collaboration with EU seaweed experts so that common rules are put forward.

Table 10 summarises different recommendations for policymakers regarding regulations or actions for supporting seaweed production in Europe.

Table 10. Specific recommendations for policy makers.

	Protection	**Regulation, compliance requirements**	**Recommendations - Governance**
FOOD	Food safety Consumers Stakeholders	Legislation on seaweed as a food supplement Legislation on heavy metals and total arsenic in feed Regulation (EC) No 710/2009 for organic certification Novel Food Catalogue	Update the threshold values of different contaminants for seaweed as food, and specifically, the inorganic arsenic threshold for feed legislation Define the core value of legislation threshold values: based on dry weight preferred (or wet weight) of seaweed for food General risk-benefit analyses of seaweed Homogenise certification systems across the EU, for example by implementing certification centres Implement sensory-evaluation panels to design a vocabulary to describe the flavour of seaweed Support industrial classification codes to describe best practices, for example for washing, drying/stabilising and storing seaweed Transparent overview of seaweed accepted as food (both authorized before and after 15 May 1997)

CHAPTER VII –

RESEARCH PROGRAMMES TO SUPPORT SUSTAINABLE DEVELOPMENT OF SEAWEED AQUACULTURE

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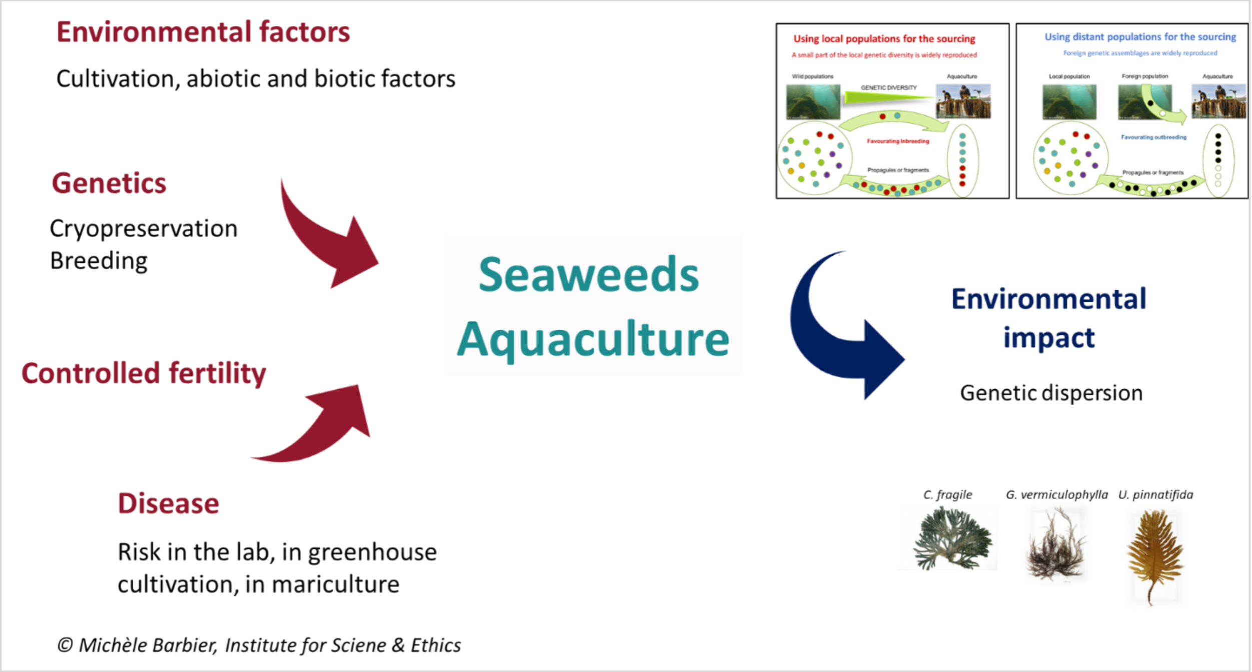
As seen in the previous chapters, seaweed aquaculture is a complex sector conditioned by environmental, biological and external factors, relying on cultivation techniques and sites which may face environmental issues, and subject to legislation and market demand. This section aims to identify the needs for scientific knowledge in the short-, mid- and long-terms, to improve and develop future techniques to sustain aquaculture of macroalgae in Europe.



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The suggestions presented in this chapter, on the R&D programmes that need to be developed shortly, are transversal to the various preceding chapters and are summarised in Table 11:

- Biological and ecological challenges relate to cultivation processes and obtention of the best cultivar, namely, how to preserve and improve selected strains.
- The impact of environmental factors (biotic and abiotic) on the physiology of seaweed is another critical aspect of cultivation technique which requires more fundamental and applied knowledge. Disease issues that call for the attention of research programmes are also covered in detail.
- Research programmes to better understand the impact of seaweed aquaculture on the environment are suggested.
- Some technological advances including methodologies are also detailed, specifically for biorefineries and IMTA development.
- More knowledge on the bioactivity and bio-functionality of seaweeds for the food market is another target of suggested research programmes (see Tables 11 & 12).
- Finally, innovation can be sharpened by bioprospecting across various scientific tools.

Table 11: To answer identified challenges, some research programmes are summarized below and detailed in the chapter.

	Challenges	**More research is needed to**
Biology of Seaweeds	Conservation of species of interest	Develop cryopreservation methods
	Improvement of strains of interest	Improve breeding & selection programmes
	The life cycle of new species	Identification of the factors influencing the fertility & reproduction of new species
	Impact of environmental factors on phenotypic traits	Understand the impact of space confinement, and the natural environment
	Impact of biotic factors	Improve the production of juvenile seaweeds.
		Identify pathogens, prevention methods and treatments Understand epiphyte blooms
	Impact of abiotic factors	Improve the shape and texture of mature seaweeds

Cultivation	Impact on the environment	Control of genetic dispersion
	New cultivation: IMTA	Optimise site locations and develop co-cultivation best practices
	New cultivation on artificial substrates	Develop an understanding of adhesion mechanisms
	Biorefineries	Improve technologies & methodologies
Food	Bioactivity & bio-functionality of seaweeds	Determine the effect of seaweeds on health
Innovation	Bioprospecting	Screen for new bioactive products

I - BIOLOGICAL & ECOLOGICAL CHALLENGES

I.1. How to control the genetics of seaweeds

I.1.1 CRYOPRESERVATION FOR CONSERVING GENETIC PATRIMONY

Cryopreservation consists of freezing macroalgal germ cells or juvenile organisms for their long-term conservation, optimally for several years. It is a technique which awaits further development because of the shortcomings of present production methods. Currently, the yearly production of juvenile seaweeds is carried out by fertilising male and female gametophytes maintained in cultivation in artificial conditions (e.g. red light for kelp gametophytes) in hatcheries for several months. In addition to requiring large volumes of recycled seawater, this process makes the cultivated genetic resources vulnerable as they are prone to contamination and diseases. Therefore, keeping seaweed germ cells and juvenile organisms dormant is an option that is cost-effective in addition to securing genetic resources. For now, both cold-preservation (“refrigeration”, e.g. at 10°C with dim light, Barrento et al. 2016) and cryopreservation (freezing at -180°C and storage at -80°C or -20°C) can be carried out on a very limited number of seaweeds. Slow-rate freezing or fast-rate freezing (vitrification) are two different methods of cryopreservation used on 25 different species of seaweeds (Day 2018).

To develop cryopreservation, specific needs in research have been identified.

HOW TO DEVELOP CRYOPRESERVATION TECHNIQUES?

Assessment and choice of the cryopreserved species. Development of cryopreservation protocols is time-consuming and very few teams are committed to such tasks (less than 30 protocols developed in the past 35 years, Day 2018). Therefore, before developing protocols, efforts must be jointly deployed to urgently identify the priority seaweeds, supported by an assessment of the genetic diversity by geographical mapping.

Development of cryopreservation protocols. There is no reliable general knowledge on the cellular and chemical mechanisms of cryopreservation, and protocols must be developed empirically for each species. Chemical cryoprotectant agents like DMSO or glycerol are commonly used in the extracellular medium. These protect the cell by diffusing into the cytoplasm and reducing intracellular water content. Chemical composition and concentrations of these cryoprotectants have to be adjusted for each species. Key components of the protocols also include the freezing speed, the final temperature before plunging the material into liquid nitrogen, the thawing procedure, and the storage duration. So far, protocols have been developed only for short storage periods of a few days to less than a year, but current development on kelp has shown a possible extension to up to two years (B. Charrier, Station Biologique Roscoff, personal communication).

This method is also most likely subject to somaclonal variation as discussed below and correlated epigenetic and possibly stable genetic changes. When freezing human embryos typically 80% dies, indicating the stress and genetic changes causing it. Genetic studies of the specimens having been through the protocol would add important understanding and background to evaluate the balance of risk / advantage of this in vitro laboratory technology.

Identification of the molecular and cellular mechanisms of cryopreservation. Formation of ice crystals is the main threat during cryopreservation as these can physically damage intracellular structures like organelles and plasma membrane, which are necessary for living cells. In addition, the specific chemical features of the many molecules present within the cells make a prediction of the suitability of the cryopreservation treatment difficult. Endogenous molecules synthesised by the cell (sugar, polyhydric alcohols, dehydrin proteins) can mitigate the damaging effect of freezing by reducing the water content to prevent the formation of ice crystals, or by covering proteins to protect them from irreversible structure modification during the freezing and thawing processes (chaperone proteins). Anti-freeze proteins (AFP) and ice-binding proteins (Kim et al. 2017 a, b) have been isolated from polar samples and shown to be hyperactive in protecting biological samples from single cells like diatoms in mammal embryos and organs during both freezing and thawing steps. However, whether these components are efficient for seaweed preservation is unknown. Therefore, further research is needed for better control of cryopreservation steps.

I.1.2 BREEDING AND OTHER GENETIC MODIFICATIONS

Natural populations generally display a wide range of genetic diversity, depending on the trait and evolutionary background. Positioned on an absolute scale, this natural diversity is limited.

The factors of limitation of genetic diversity are:

- Non-interaction of sexual partners because of environmental niches which are distant and separated geographically.
- Incompatibility (physical or genetic barriers preventing fertilisation or embryo development).
- Slow (at human timescale) genetic-drifting rate, due to the impairment of DNA repair occurring at each cell division, itself impacted by environmental stresses.

Domestication has long been developed to improve seaweed traits in Asian countries, and occurred through breeding (here, implying crosses). If parental breeding strains are too close genetically, and the size of the offspring population too restricted, this approach could lead to inbreeding depression (refer to Chapters III & IV on breeding for details and references). It is, therefore, important to secure regulatory guidelines based on the current knowledge of seaweed population genetics of the respective species, to allow cultivated and wild populations to thrive.

While breeding aims to improve ToI, it can lead to loss of ToI and even new phenotypical defaults because of genetic depression *(see Chapters III and IV on Seaweeds production and cultivation, section genetic depression and heterosis).* These effects vary from one species to another, together with the genetic distance between two parental lines, and can limit the range of possible crosses for selection programmes or improvement of cultivated strains. Such breeding effects may also severely impact natural populations if farms are located in close vicinity to wild populations. This issue has already been discussed in Chapter IV.

Besides breeding, a few genome-modification approaches have been developed for several species of seaweed, inspired by protocols developed for animals and land plants. These employ a variety of techniques involving different effective agents (chemical, physical, biological) and algal tissues as initial materials. The impact on both seaweed genomes and seaweed traits should be considered in the assessment of the most appropriate technique. Most of these techniques do not enable targeted and controlled modification of the seaweed DNA. While scientifically effective and useful for fundamental-research purposes, they are controversial as methods for improving cultivated seaweed.

- **Genetic transformation** (also named transgenesis) is a technique that introduces any kind of DNA into a host cell. This is typically a DNA construct made in a laboratory, containing two to ten genes of interest for research or breeding purposes. The DNA can be of a different origin than the host cell/organism (in this case, named “foreign”), and can either be inserted into the genome of the host cell (stable transformation) or be non-inserted while remaining in the cell. While in the former case the DNA is transmitted to daughter cells and to the algal progeny, in the latter, the DNA is lost usually after some cell divisions. It is currently possible to stably transform the green seaweed *Ulva* using a poly-ethylene-glycol-based protocol (Oertel et al. 2015), and potentially the red seaweed *Pyropia yezoensis* (Hirata et al. 2014) and the brown seaweed *Laminaria japonica* (Li et al. 2009) using a biolistic approach consisting in bombarding the seaweed thallus with DNA-coated particles. Examples of the transient transformation of seaweeds are reported in Mikami et al. (2014). Other ways to insert DNA into a plant organism exist, like the *Agrobacterium*-mediated stable-transformation system (based initially on a natural recognition process between plants and bacteria), electroporation (using fast and high electric pulses depolarising the cell membrane and allowing DNA entry), and transfection (using a mix of chemicals and proteins to help DNA entry).

These techniques generate what is named “genetically modified organisms” (GMOs). Unless they are eliminated by several steps of crosses with a wild organism (back-cross), GMOs contain several copies of the DNA construct in their genome. Currently, the release of GMOs in the environment is regulated by the European Directive 2001/18/EC while the importation for consumption of genetically modified food and feed is under Regulation (EC) 1829/2003. Following risk assessment by the European Food Safety Authority (EFSA), the European Commission will grant (or not grant) approval.

- **Mutagenesis** consists in exposing cells or tissues to a mutagenic agent (Ultraviolet (UV) light, or chemical agents like Ethyl methanesulfonate (EMS)), and results in hundreds of mutations spreading throughout the genome. It has been employed for red, green and brown seaweeds (reviewed in Charrier et al. 2015) and can produce seaweed with higher yields and higher stress resistance compared to wild organisms (Ma et al. 2019). Organisms mutagenised with UV or EMS do not fall under the scope of the European GMOs Directive.

- Genomes of two organisms which cannot cross naturally (through reproduction) can be mixed together by **somatic hybridisation**, a process using an electrical field or a chemical agent (polyethylene glycol (PEG) to force cell fusions. In seaweeds, it usually results in unstable and massive trait modifications (reviewed in Charrier et al. 2015; also refer to genetic depression, described above).

The development of all these techniques is species-dependent and requires several years of research. Therefore, additional development of cutting-edge techniques (e.g. genome editing, GE, see below) is needed in order to answer the challenges raised by the industry today.

HOW TO IMPROVE BREEDING?

Identification of Traits of Interest (ToI) / Quantitative Trait Loci (QTL) - assessment of their stability in population dynamics.

Defining and agreeing on what an "interesting trait" is requires different levels of analyses and a multidisciplinary approach:

- *Variability and distribution*: The first step is to explore the variability of the existing values for the ToI within and between wild populations. In this respect, better knowledge of the geographical distribution of this variability is needed. This could be reached by a combination of prospections, sampling and environmental monitoring before running Geographical Information System (GIS) applications of all the collected data.

- *Determining targeted traits:* The second step is to identify the relative importance of genetic versus environmental influence over this variability (i.e. determinism of the trait): i) If the expected value for the targeted trait is mainly under local environmental control, farmers will only be able to cultivate local strains or strains from a population with similar conditions; ii) If the targeted trait is mainly or exclusively the effect of robust gene expression independently of external factors (i.e. genetic determinism), a genetic approach is needed to determine the gene variants (alleles) that are related to the expected value for the ToI. In some cases, quantitative traits (length, width, weight, number of propagules…) are dependent on the expression of a high number of genes (i.e. Quantitative Trait Loci, QTL) and the "best" allele combination is difficult to identify. Several experimental methods, requiring both a population of offsprings and molecular markers (DNA sequences) allow listing the different allele combinations of the genes responsible for the traits (Varshney et al., 2016).

This process is long-term.

Assessment of the genetic distance between parental lines. Obtaining an abundant and safe offspring displaying the requested properties requires having the optimal genetic distance between crossed strains. In order to select optimal parents, the genetic distance should be assessed, most efficiently through genomic analyses. Knowledge of the genome sequences of cultivated seaweeds speeds up molecular-based selection techniques. *Ulva* and *Saccharina* genome sequences have been recently published (de Clerck et al. 2018 and Ye et al. 2015, respectively).

Assessment of the impact of breeding on natural populations. This assessment depends on two main factors.

i) The dispersal potential of (newly) bred lines depends on the capacity of the juvenile seaweed to resist drifting from their cultivation area and their ability/fitness to get established in wild populations' areas. This event is accentuated by the capacity of seaweed to reproduce by thallus fragmentation or parthenogenesis, and to resist harsh conditions for a long period.

ii) The capacity of (newly) bred lines to reproduce/cross with native, local populations. To assess the impact of newly bred lines on wild populations, better knowledge must be acquired on reproductive strategies (autogamous, allogamous, random mating…), and also the level of cross-compatibility between strains/populations for each cultivated species. Likewise, research programmes assessing the most extreme conditions (ecological barriers of reproduction) that relevant seaweed tissues and cells can resist to should be planned.

Genome modification. Genome editing (GE) seems to be a promising technique, as it potentially allows targeted single-nucleotide modification ("point mutation") of an organism's genome when carried out via homologous recombination (Puchat 2017).

GE is currently based on the activities of defence molecules (proteins, RNA and DNA), usually of viral origin, that target bacterial DNA. These molecules are modified to recognise selected sequences and subsequently knock out these genes' effects. Several methods exist, like TALEN and CRISPR-Cas9 (see review in Bortesi & Fischer 2015). While already developed in microalgae (Gan & Maggs 2017), none is efficient on seaweed so far. The first prerequisite is a functional transformation method and preferably a fully sequenced genome. When directly introduced into targeted cells (e.g. through microinjection), the activity of these molecules can result in a single nucleotide mutation. However, several off-target mutations can be observed at other locations in the genome, prompting current research on how to eliminate or avoid them (Puchat 2017).

The first experiments are currently being undertaken in a pair of seaweeds and further development is necessary to explore the potential success of this technique.

The precautionary principle needs to be followed before any genome modification. Before using genome editing to develop cultivars for mass production, the full potential and risks of any product should be evaluated on a case-by-case basis. Since July 2018, GE organisms are subject to the GMO legislation delivered by the Court of Justice of the European Union (see above for specific legislations relative to GMOs). In the future, GE cultivars may be regulated differently depending on how risk assessment evolves.

I.1.3 CONTROLLING FERTILITY, REPRODUCTION, LIFE CYCLES

Some seaweeds of commercial interest cannot reproduce or even grow in artificial conditions. Subculturing (by fragmentation, clonal propagation, cf. *Gelidium*) is not feasible. Environmental factors inducing spore production and fertility of gametophytes have been identified experimentally for some seaweeds (see Charrier et al. 2017 for a review). This allows control over the production of juvenile sporophytes in hatcheries to some extent. However, in some species like *Palmaria palmata*, the spore-germination rate is low, with over 80% of spores decaying within a few hours. Consequently, this requires the seeding of the culture substrate by excess fertile sporophytes and prevents the establishment of a quality standard for aquaculture practices.

HOW TO CONTROL FERTILITY?

Develop protocols inducing fertility in controlled growth conditions. In the short term, this can be undertaken on an empirical basis, by testing a range of environmental parameters including the light, temperature, and the supply of organic and inorganic compounds in the cultivation sea water.

Identification of factors inducing fertility. Research is needed to understand the relationship between the biochemistry and health of fertile sporophytes and spore-germination success. This would provide criteria to select the best blades to get the best spores, thus increasing the productivity of seaweed hatcheries and reducing the waste of wild sporophytes.

Interestingly, recent research has shown that in the genus *Ulva*, marine bacteria play an essential role in morphogenesis and growth (Wichard et al. 2015). Research should assess whether bacteria also control the fertility of cultivated seaweeds, which would make the sterilisation of seawater and culture medium, currently carried out in seaweed hatcheries, counterproductive.

I.2. Physiology of seaweeds: impact of environmental factors on phenotypic traits

I.2.1 Impact of cultivation confinement/space on the seaweed growth rate

Studies have shown that cultivation parameters impact seaweed growth. In land-based facilities, seaweed cultivation is usually carried out in confined containers (either outdoor tanks or hatcheries). Regarding the tumble-culture conditions provided for some species like dulse (*P. palmata*) in tanks (indoor or outdoor), each laboratory uses its culture set up, and huge uncertainties surround the optimal thallus concentration vs tank section (surface), water volume, water-inflow rate, temperature, illumination and frond-circulation rate. Whether the set-up culture parameters should be maintained over the different life stages of the cultivated seaweed (e.g. tetrasporophyte and male gametophyte of *P. palmata)* is also unknown.

Several reports, now reaching scientific conclusions about seaweeds grown in tanks, are unverified or even contradictory when seaweeds are cultivated in the open sea. See examples in the sections below.

MORE RESEARCH ON THE IMPACT OF SPACE CONFINEMENT MUST BE CARRIED OUT.

I.2.2 Impact of abiotic factors – light, temperature, nutrients – on the production of juvenile seaweeds

In hatcheries, optimal temperature, light quality and intensity for the production of juvenile kelp are all identified (Forbord et al. 2012; Kumura et al. 2006; Peteiro et al. 2016a & b). Light (wavelength and/or intensity) controls both the density of branches of kelp gametophytes (Pereira et al. 2011), which may impact the overall capacity of the whole organism to adhere to the spool, and their shift to the reproductive phase (reviewed in Charrier et al. 2017), impacting the time management of the production of juvenile sporophytes. Besides light and temperature, elevated CO_2 (Xu et al. 2008), iron (Lewis et al. 2013), nutrient enrichment and growth inhibitors (Kerrison et al. 2016) all impact the settlement and growth of gametophytes and juvenile sporophytes.

HOW TO IMPROVE THE PRODUCTION OF JUVENILE SEAWEEDS?

More research about the impact of environmental factors must be undertaken, especially by combining factors rather than studying them independently from one another.

Integrative modelling approaches should be developed to anticipate the impact of multiple factors.

I.2.3 Impact of abiotic factors – sea currents – on the shape and texture of mature seaweeds

The morphological plasticity of seaweeds has several consequences for seaweed cultivation. Smooth frond surfaces may, in response to turbulent conditions (i.e. high hydrodynamic forces), turn into bubbly surfaces, causing higher drag forces on cultivation platforms. Similarly, significant data shows that hydrodynamic forces also influence cellular composition: seaweeds growing in turbulent waters have higher percentages of carbohydrates (i.e. structural components) than those growing in sheltered niches. Most seaweed research on hydrodynamic effects has focused on either morphology or biomechanics (D'Amours & Scheibling 2007; Koehl et al. 2008; Demes et al. 2013; Vettori & Nikora 2017), while those on the availability of nutrients (enrichment and seasonal fluctuation) have mostly focused on morphology rather than on biomechanics (Espinoza & Chapman 1983; Spurkland & Iken 2012; Boderskov et al. 2016). Few studies are available on the interactive effects of hydrodynamics and nutrients on the morphology and biomechanics of seaweeds. This lack hampers insight into how seaweeds survive in habitats with varying hydrodynamics and/or availability of nutrients. The commercially exploited seaweed *Saccharina latissima* is highly plastic in response to environmental factors. Wave exposure in particular results in modified frond morphologies and biomechanics, while the availability of nutrients has only a slight influence (K. Timmermans, unpublished).

HOW TO IMPROVE THE SHAPE AND TEXTURE OF MATURE SEAWEEDS?

More research on the impact of mechanical forces together with nutrient availability on seaweed physical traits must be carried out.

I.2.4 Impact of biotic factors – bacteria, endophytes, epiphytes – on seaweed health

The pervasiveness of seaweed-accompanying microbes (a.k.a. holobiont), some virulent to their algal host, is becoming increasingly evident. Understanding on how seaweeds respond to infection is incipient, with reports on just a few defence mechanisms such as oxidative stress and some metabolic and transcriptomic regulations (Cosse et al. 2007; Grenville-Briggs et al. 2011; Strittmatter et al. 2016). An extra layer of complexity in algal-pathogen interactions is added by the combined effects of diseases with disruptions from biological (grazers, competitors, other pathogens) and anthropogenic (i.e. global warming, ocean acidification, water pollution) origins, both of which are rarely investigated as potential threats for seaweed aquaculture. Establishing host-pathogen lab models amenable to the investigation of the pathogenicity of algal pathogens and the defensive mechanisms of (cultivated) seaweeds is key to the design of proper disease-management guidelines in the future. Significant advances in human, animal or plant disease research have been achieved by establishing lab models (pathosystems) which share features such as minimalist, parallelisable and easily maintainable/reproducible propagation. So far, many algal pathogens have been described (Gachon et al. 2010), although only a few pathosystems have recently been properly isolated/transfected on lasting cultivable strains (Carney & Lane 2014). One important challenge has been to keep alive and propagate these pathosystems on a laboratory level. This may be extremely difficult due to the nutrition strategy of the pathogens (some are strictly obligate, such as the oomycete *Eurychasma* or the phytomyxid *Maullinia*), or their very restricted host specificity (like *Anisolpidium rosenvingei*, which has been found to infect reproductive cells in *Pylaiella littoralis*).

HOW TO OVERCOME THE ISSUE OF EPIPHYTE/EPIBIONTE DISEASES?

Identify and characterise the diversity of infectious agents associated with seaweeds in mariculture and wild populations. In order to determine which biological threats exist, metabarcoding/metagenomic surveys need to be conducted on seaweed farms to screen disease symptoms and their associated pathobiome. Aetiological studies looking for disease proxies based on morphological, physiological, metabolic and transcriptomic changes should be targeted at this stage. A similar approach should be carried out on natural populations, which could help to detect potential disease reservoirs or hotspots for mariculture-to-natural stock disease transfer.

These results may also contribute to the standardisation of monitoring methodologies, and to guidelines to be adopted by reference laboratories. They will also be the basis of biosecurity policies for seaweed mariculture facilities.

Establish host-pathogen lab models amenable to the investigation of the pathogenicity of algal pathogens and the defensive mechanisms of (cultivated) seaweeds. A first step should include an understanding of the life cycles of yield-limiting pathogens. Techniques need to be developed to standardise continuous cultures for both pathogen and algal host. Once these laboratory systems are available, studies on the interaction may be carried out at a cellular, physiological and molecular level, with emphasis on the virulence of the pathogen, the resistance/susceptibility in the host, and disease management.

Development of disease-resistant strains of economically important seaweeds. In parallel to the aim in Section I.1.1 of this chapter (“Cryopreservation for conserving genetic patrimony”), one criterion for strain selection should be the extent of resistance to certain diseases. This can be achieved by the standardisation of techniques to quantify resistance, in both laboratory and field conditions. This need is also linked to the elucidation of resistance mechanisms. Seaweed strains should also be tested for agronomical traits such as growth (i.e. biomass, growth rate) and industry-related metabolites (i.e. pigments, sugars), in order to ascertain to what extent productivity is compromised by immunity in a potential tradeoff between the two.

In parallel, these strains may be mined for resistance genes using genomic tools. Such knowledge is not only crucial to understand immunity in the hosts but also to develop long-term breeding programs in seaweed aquaculture with disease-resilient parents. In this respect, Genome-Wide Association Studies, which are now mainstream in land agriculture, are just beginning to be implemented on European seaweed species. This technology has enormous potential to accelerate the domestication and breeding of disease-resistant algae while minimising conservation issues such as drastic loss of genetic diversity due to linkage disequilibrium, compared to traditional breeding techniques (i.e. backcrossing).

Identify methods to prevent infection and propagation. Research work is primarily needed to identify the source of infection. Even though the first recommended action in farming affairs is husbandry, mitigation strategies after outbreak events should also be investigated. This research should be directed towards: *i)* boosting the immune system, which consists in identifying which conditions may efficiently prepare a seaweed to better face the potential threat of a pathogen; *ii)* blocking or killing the pathogen using chemicals. This requires investigation into all potential chemicals that can be applied to infected organisms, and their potential consequences both on pathogen resistance and on the environment. Alternatively: *iii)* seaweeds naturally have beneficial symbionts, microbes that are very important in combating pathogens in the wild (Prado et al. 2017). Similar to biocontrol methods used on land, this novel approach is yet to be exploited commercially. It may, however, offer greater environmental sustainability in comparison with the other approaches.

Designing biosecurity policies and protocols for farm facilities is key to reducing and managing any disease outbreaks (*see Chapter IV on Challenges in seaweed cultivation process*).

I.2.5 Seaweed phenotypic traits: from growth to the metabolome

The metabolomic pattern of cultivated seaweeds is one of the reflections of their general status during growth and in changing environments. Metabolomics is one of the emerging areas of functional genomics and provides new insights into systems biology (Gupta et al. 2014). This approach provides an inventory list of chemicals produced in response to specific treatments during aquaculture. Along with the available seaweed genomes, the integration of metabolome with transcriptome analysis will shed light on gene functionality and its regulation. Indeed, the impact of many factors (e.g. environmental stimuli, lifecycle changes, epiphyte infection, biofouling) can be assessed by comparative metabolomics, and biomarkers can be found indicating changes in, e.g. developmental or health status. Based on this knowledge, aquaculture conditions, control of life cycle and harvesting periods can all be better managed.

Many laboratories are now equipped to perform metabolome studies through UHPLC-HR-ESI-MS and GC-HR-MS analysis. Convenient pipelines for data processing and analysis are available (e.g. XCMS; Workflow4Metabolomics, and metabolomics have become a common tool in seaweed research.

However, current challenges remain in: *(i)* the identification of unknown metabolites/biomarkers (i.e. no reference molecule is available for comparison); *(ii)* the combined analysis of metabolomic datasets along with transcriptomic and proteomic analysis; and *(iii)* the reproducibility of data. Therefore, standardised culture conditions are essential to obtain reliable biomarkers even from seaweeds grown in large volumes (Alsufyani et al. 2017; Kessler et al. 2017; Kuhlisch et al. 2018). Protocols are set up for *Ulva* and other macroalgae at small volumes for e.g. the analysis of copper-stress acclimation in *Ectocarpus* (Ritter et al. 2014) and the exo-metabolome profiling under standardised conditions of axenic versus non-axenic cultures in *Ulva* (Alsufyani et al. 2017). Overall, only a few studies have been published and therefore, the research field has to be further developed, for example, as part of algal phenotyping for aquacultures (Fort et al. 2019).

II - ENVIRONMENTAL IMPACT OF SEAWEED AQUACULTURE

II.1 Genetic dispersion

Because cultivated populations are obtained from a low number of wild individuals, they represent a small part of the existing variability. As a result, genetic diversity within cultivated populations is lower than within wild populations. If genitors from farms manage to cross successfully with wild populations, they risk spreading reduced genetic diversity to the latter. In this way, through the effect of inbreeding/outbreeding depressions, the wild-population dynamic stability can be disrupted. Ultimately, this would induce a progressive decrease of wild genetic diversity up to the point of the population's extinction. As a result, no more sourcing would be available for farmers. The challenge hence consists in preventing any genetic connection between farms and wild populations. However, it is very difficult to control the escape of individuals and/or propagules, especially for at-sea farms.

HOW TO CONTROL GENETIC DISPERSION?
Better knowledge of **species reproduction and dispersal processes** (modes, distances, periods).
Comparison of the genetic diversity and genetic structure of both cultivated and wild populations; evaluation of gene flows between farms and wild populations. A possible technical solution for the limitation of gene flows would be: *i)* the physical isolation of the cultivated populations; *ii)* the deployment of "technical itineraries" (i.e. delayed cultivation times to desynchronize the reproduction period), and, *iii),* under certain conditions, the availability of sterile cultivated strains.

II.2. IMTA: Seaweed-(shell)fish co-culture

Integrated Multi-Trophic Aquaculture (IMTA) is the co-cultivation of seaweeds and fishes and/or shellfishes that are connected by matter flows. It aims to be beneficial at different levels: trophic benefit for the cultivated species, environmental benefit through the reduction of waste and economic benefit through the production of potentially high value products.

In some countries, seaweeds are primarily cultivated in bays dedicated to shellfish farming or on existing shellfish farms (US, Canada) or salmon farms (Norway). In some cases, the seaweeds (kelp in this case) share culture long lines with invertebrates *(for details on IMTA see Chapter III on Seaweed production and cultivation).* There is very little information on the mutual benefits or drawbacks of kelp-mussel co-cultivation. Knowledge is required in order to better advise farmers and aquaculture-development agencies on how to proceed with this approach.

HOW TO SUPPORT IMTA DEVELOPMENT

Identification of the best cultivation sites for IMTA.

i) Case by case definition of the optimal distance between IMTA-cultivated organisms (fish, shellfish, seaweed): adequate distance to optimise both remediation and growth stimulation.

ii) Congruence of the cultivation sites: the same marine environment is not necessarily optimal for all species, in terms of exposure, nutrient concentrations and salinity.

Better documentation of the effects of co-cultivation of seaweeds and shell-fishes about:

i) Temporal convergence in co-cultivation: documentation for increased water clarity due to mussel filtration, reduction of biofouling as a consequence of mussel filtration, mussel release of inorganic nutrients taken up by seaweeds.
ii) Temporal divergence (mussels, spring-autumn – kelp, autumn-spring): technical and economical benefits from the use of cultivation structures/areas and equipment/boats for dual crops; avoidance of settling of mussel larvae on seaweed lines.

Investigation of potential direct and indirect effects of seaweed co-cultivation on animal health (including cultivated fishes and wild animals), reproduction, growth and behaviour, about:

i) Seaweed exudates of bioactive compounds;

ii) Alteration of microbial and phytoplankton diversity and community composition;

iii) Bulge of harmful organisms: e.g. sea lice can be eaten by bivalves (mussels), preventing their profusion on marine fishes, and also preventing the usage of treatments like chemical agents that negatively impact on wild sea worms.

Optimisation of cultivation practices

i) Compatibility of the infrastructures for seaweed and (shell)fish cultivation;

ii) Amenability of the harvesting process, concerning the co-cultivation device.

Coordination of legislation/licensing of all marine aquaculture organisms by one single authority.

Space management, species combinations, impact on the environment, regular and long-term biomitigation should be taken into consideration.

II.3. Impact on animal wildlife

Many animals share the same environment as seaweeds, among them marine mammals, fin- and shellfishes, molluscs and worms, and birds. Attention should be paid to the impact of seaweed aquaculture on their growth and reproduction, through the development of specific long-term ecological research programmes.

III - TECHNICAL SCIENCES AND BIOTECHNOLOGIES

Technical development must accompany the improved handling and management of seaweed due to progress in biological knowledge.

III.1. Geographical mapping

A GIS (Geographic Information System) is a tool that allows the combination of different mapped data for spatial and spatio-temporal analyses (Malczewski 1999). It enables the overlay of information such as the geolocation of production sites, the distribution of natural algal populations and environmental quantitative data (temperature, sun exposure, current, salinity…). Because the characterisation of local wild resources and the identification of optimal farm sites (whether at-sea or land-based) are identified challenges for the development of seaweed aquaculture, GIS is required for the development of predictive and monitoring tools. To be fully efficient, GIS needs to be frequently updated with new data.

Therefore, research is needed to:

- Identify the type of data that should be considered as the most relevant.
- Develop methods and devices that allow the production of this relevant data.
- Improve the numerical platforms and networks that can store and share the data.
- Upgrade existing GIS software to boost the capacity to combine complex data.

III.2. Cultivation-technique engineering: Adhesion on artificial substrates

Knowledge is scarce about the physical mechanisms underlying the colonisation and resilience of seaweeds in their environment. In the context of aquaculture, these issues are of particular significance, as the entire kelp-production process, from the early stages to the harvest of the total biomass, depends on the seaweed's adhesion to artificial substrates (spool, ropes, concrete substratum). Recent studies have started to show how adhesion could be increased by manipulating the growth medium and the surface of the substratum (Kerrison et al. 2016), or by selecting specific genotypes showing different densities of adhering tissues (Pereira et al. 2011). Once transferred to the sea, seaweeds are exposed to very high mechanical forces (currents, tides, storms, waves; up to 30 km h^{-1}, density 1000 times higher than the air), and one major problem for the aquaculture of seaweeds cultivated in energetically exposed environments is the loss of biomass due to dislodgement from the cultivation lines. Improving the adhesion of kelp to their substratum, and their resistance, will prevent loss of biomass due to storms and strong sea currents. Substratum characteristics such as chemical composition, colour, texture, and surface topography have all been shown to be potentially influential for the settlement and recruitment of invertebrates and seaweeds. Microscopic observations show that seaweeds excrete a compound enabling adhesion to their substratum. The chemical characterisation of these compounds, not yet achieved, will provide important knowledge resources for the development of natural glue resistant to seawater (Johnson 1994).

HOW TO DEVELOP ARTIFICIAL SUBSTRATES?
Identify molecular markers to assist the selection of the most adherent seaweed cultivars.

Select the most efficient/relevant artificial substrates. Technologies like light microscopy, Scanning Electronic Microscopy, Atomic Force Microscopy, RAMAN, Mass Spectrometry, can be used to characterise the physical and molecular features of the substratum.

The impact of the artificial substrates on the natural environment must also be assessed before massive deployment in the sea.

Characterise, at a chemical level, the natural adhesive compounds secreted by algae, and assess the extent to which they could reinforce the attachment of juvenile seaweeds onto the cultivation substrate.

Beyond the chemical characterisation of this adhesive mucilage, **assess the impact of environmental parameters** (time, temperature, stress, pH) on the secretion of natural adhesive compounds by the alga (at the laboratory level).

III.3. Biorefinery (proteins, pigments, fatty acids, vitamins, antioxidants)

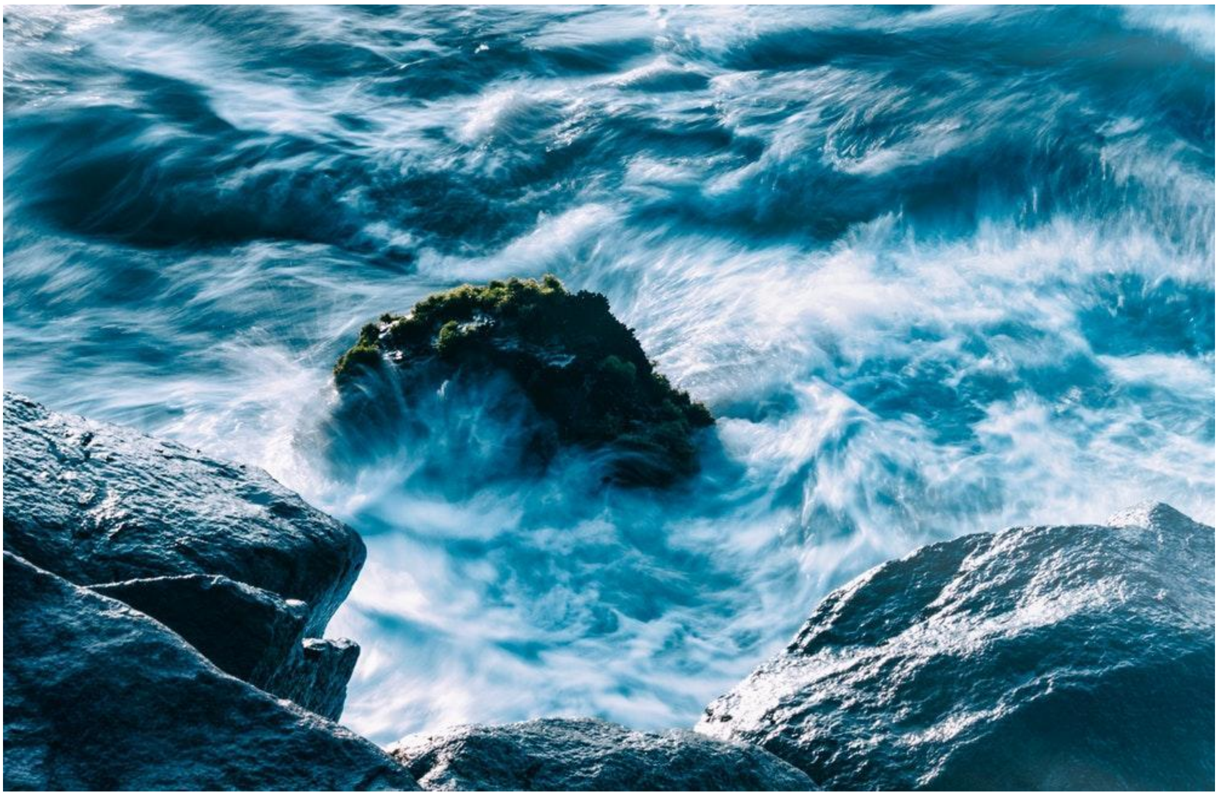
A challenge is to educate the public/industries/decision-makers to understand that no simple solution exists for algal biorefineries (and to sharpen discernment on the urge to "jump on the bandwagon"): the concept is often oversimplified as these biorefineries are easily communicated as offering a low-cost integrated solution to most current global challenges (food/protein supply, carbon sequestration, water-quality improvement, multiple products). While this is an ideal situation, the reality of upscaled algal production and processing is more complex, and actual production costs and quality of products need to be balanced and linked to operational scales.

HOW TO SUPPORT BIOREFINERY DEVELOPMENT?

Improve technologies. Improve separation and analytical technologies for high-value compounds, focusing on species with potential for biomass upscaling but also rarer species with high potential for which upscaling may be achieved in the future

Improve methodologies. Improved methodologies for life cycle assessment that can be applied to different types of algal production systems and biorefineries.

More research on valorisation. Further investigation into the valorisation of biomass residues after extraction/separation of high-value products, and investigation of new side-streams for high-value products to ensure a stable market.



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IV - FOOD SECURITY AND MEDICAL CONCERN

IV.1. Health

Clinical trials on the impacts of eating seaweed should be carried out regularly as more knowledge is necessary to define the risks and benefits of such consumption.
Research, especially on shelf-life, must be performed at the national or EU levels, on both short and long terms. Studies can be initiated with a group of commonly eaten seaweeds, and progressively focus on the most abundant or most potentially harmful/beneficial compounds.

IV.2. Bioactivity/Biofunctionality

Despite a plethora of research outputs regarding reported bioactivities of algal extracts and compounds, the translation of scientific knowledge on health-promoting activities into commercial products is currently hindered by several obstacles. Amongst others, reported biofunctionality stems predominantly from *in vitro* experiments, sometimes extending to the gut (for example) or animal models, but human intervention studies (human trials), or studies on other final application systems have only rarely been conducted. Only a (relatively) small number of algae have been analysed systematically (rather than opportunistically) and results are sometimes contradictory; this is in many cases linked to the broad plasticity of algal compounds with potential bioactivity. As a result, small variations in chemical composition induced by environmental fluctuations, or synergistic effects of several compounds present in the seaweed, can have significant impacts on both bioactivity and bioavailability.

It is often not clear if reported bioactivity is linked to individual compounds, or combined effects of different compounds in non-pure extracts. Therefore, the stability of bioactivity and bioavailability of compounds requires further research. Interactive effects with or direct effects on the digestive system including gut microbiomes of populations (and individuals) at different life stages (or stages of health) are largely unknown. Negative (either inactive or detrimental) effects of algal compounds are rarely reported in the literature.

TO IMPROVE BIOACTIVITY AND BIOFUNCTIONALITY OF SEAWEED	
Investigation of methodologies	**Investigation of methods to improve stability and to maintain bioavailability during extraction, processing and storage of algal compounds and extracts.**
Controlled conditions	**To obtain stable, high-value products, commercial production of seaweeds for high-value applications needs to be conducted under controlled conditions to avoid chemical variability**. Research should address potential mechanisms to creatively reduce cost (including energy consumption) of on-land cultivation to allow the development of algal production, the equivalent of "greenhouse" horticulture of land plants and conventional food crops.
Bioactivity	**Investigations into the loss of bioactivity in purified extracts vs non-purified extracts;** investigation of bioavailability and interactive effects of different compounds (especially if non-purified extracts or intact algae are used); studies performed *in vivo* and involving humans; requirement for time- and cost-effective protocols; avoid the publicising of unsubstantiated claims that may put the consumer at risk but also in the long-term damage the reputation of the sector.
Potential negative effects	**A critical but honest evaluation of potential adverse effects of algal products** (for various applications, focusing on food in the first instance), other than that of toxic algal-bloom effects which are at least partially documented and managed. These include potential direct toxic effects of compounds as well as a thorough assessment of side effects and interactive effects. The chemical effects of toxic metals for example, different forms of elements (e.g. As) and overdosage (e.g. consumption of iodine and other halogenated compounds) are of concern, but due to difficulties in chemical characterisation, levels of such compounds in wild or cultivated algae, and even more the case in algal extracts, are not well known. Therefore, the potential negative effects are poorly documented.
Education	**Education of relevant sectors/industries and regulation of health claims**; awareness and investigation of interactive effects of compounds contained in food supplements and neutraceuticals.

Standardisation	**The requirement of standards and definitions for chemical compound classes, activities, traceability, and standards for methods and claims** (e.g. organic), amongst others (currently in progress through CEN, the European Committee for Standardisation).

IV.3. Bioprospecting

Global bioprospecting activities have exponentially increased over the last few decades in response to both scientific and commercial drivers, including the need for new sources of chemicals. The focus has been on the discovery of new drugs from marine including algal sources, with a recent emphasis on addressing the urgent need for new antimicrobials, but also the search for cures for serious illnesses including cancer, diabetes, heart disease and malaria.

Common issues that tend to undermine such promising advances are the requirement of long-term investment to secure necessary human trials and the development of new compounds into commercial drugs, but also the establishment of a sustainable supply of relevant compounds which may require synthetic chemistry approaches. As a result, many recent advances in bioprospecting have not survived the "valley of death".

FURTHER ACTIVITIES NEED TO BE SUPPORTED FOR BIOPROSPECTION	
Bioactivity	**A better understanding of the linkage between composition and bioactivity is needed**, especially for species where bioactivity of the whole alga has been reported; where bioactivity has been linked to pure compounds (e.g. specific carotenoids), new sources of compounds should be investigated to secure supply and potentially broaden applications in the future.
Screening	**More screening should be undertaken in close collaboration with biologists who can discern potential changes in metabolic profiles** (rather than random bioprospecting of samples); targeted screening of groups of algae with high potential even if they are not available at large quantities or with easy access.
Algal growth and development	The current utilisation of seaweeds is limited to a few species that are easily harvested from natural populations or can be cultivated at a large scale (with a focus on open-sea cultivation); however, as it is highly likely that more new compounds/products will be found from previously understudied (and potentially rare and obscure) species, **research should address basic biological knowledge of algal development, reproduction and productivity that will underpin the sustainable exploitation of new species.**

Screening for bioactivity	**The requirement to screen algal extracts and compounds where marine/algal samples have so far not been tested**; the need for the future development of new high-throughput tests for bioactivities related to emerging human diseases or conditions where recent advances in health and food sciences have indicated the potential for natural-product applications.

Table 12: Summary of recommendations for research-funding agencies to support industry development.

For sustainable development	Means of protection Environment & human health	Challenges for the industry	Recommendations – Research programmes
Protect marine biodiversity	Prevent genetic changes, prevent dispersion, maintain local genetic resources	Selection of best location for cultivation, domestication of local strains, use of indigenous species Selection of locally adapted traits	Define geographical limits, more knowledge on reproduction, dispersal processes (distances, seasons, periodicity), the biology of seaweed: growth, reproduction, physiology, metabolism, pathology Development of selection/breeding programmes under controlled conditions Cryopreservation
	Maintain European and worldwide genetic resources	Master seaweed reproduction and fertility	
	Mitigate the impact of natural-stock harvesting on the wild environment	Apply cultivation protocols adapted to the local environment & strains	Transfer best practices to newly cultivated species, assess the long-term impact of climate on cultivation (involving multi-factorial modelling) Understand the dynamics and stability of the domestication processes Assess the impact of IMTA & offshore farming on the natural environment

	Mitigate the impact of natural-stock harvesting on the wild environment	Apply cultivation protocols adapted to the local environment & strains	Transfer best practices to newly cultivated species, assess the long-term impact of climate on cultivation (involving multi-factorial modelling) Understand the dynamics and stability of the domestication processes Assess the impact of IMTA & offshore farming on the natural environment
Increase offer flow, reliability & diversity	Non-intensive farming IMTA Biorefineries	Control/treat pests & disease. Cultivation practices for stable and reliable production	Identify pest/disease resistance of specific species More knowledge on life cycles of specific species, reproduction, seasonality Optimisation of practices Bioprospection
Food market	Food safety Healthy products	Secure food security: surveillance of arsenic, iodine, heavy metals, potentially undesirable compounds Impact of post-harvest handling (preservation treatments) on the quality & stability (organoleptic properties, nutrient content) of seaweeds Meet the food market	Standardisation & definition of chemical compound classes, activities, traceability, speciation of iodine chemical form, species identification Effects of treatments on biomass preservation, the definition of best storage procedures & best practices to evaluate product shelf-life Risk-benefit analyses on health

CHAPTER VIII –

CONCLUSIONS - SUMMARY OF RECOMMENDATIONS FOR THE SUSTAINABLE DEVELOPMENT OF SEAWEED AQUACULTURE IN EUROPE

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Photo credit: Dima Visozki from Pexels

Seaweed plays a key ecological role in coastal ecosystems and can be used for various applications. The development of the seaweed aquaculture sector can help to address global challenges related to human consumption, health, aquaculture development and management, and sustainable circular bioeconomy. The global seaweed industry has a total estimated value of €8.1 billion per year (Bixler & Porse 2011; FAO 2015) and is continuing to expand. Yet the rapid expansion of this industry can have unforeseen ecological and societal consequences. The lack of biosecurity measures and global legislation governing the cultivation and movement of seaweeds between regions and continents has been identified as one of the main challenges to tackle in order to safeguard a sustainable seaweed industry (Cottier-Cook et al. 2016).

Although European marine flora displays one of the highest species-diversity levels in the world, its seaweed production in Europe is still in its infancy. Meanwhile, interest in seaweed's many industrial applications is on the rise. There is, therefore, a need to support industries in the development of European seaweed aquaculture sustainably.

Markets show increasing interest in seaweed resources and their potential role in European Blue Growth and Bioeconomy. The development of seaweed aquaculture thus involves, in the medium and long term, the expansion of cultivation at sea due to the unlimited space offered by the latter. However, offshore cultivation may bring meaningful impacts on the environment and on biodiversity owing to the risk of escape of propagules with the potential to affect local genetic biodiversity. The need to establish a framework for the sustainable and profitable development of European aquaculture is the *impetus* for these recommendations based on scientific expertise and identification of the challenges and bottlenecks currently preventing this sector's development.

To support the sustainable development of seaweed aquaculture, all stakeholders – industry, farmers, researchers and policy-makers – must collaborate to establish European strategic-development plans. The sector is multidimensional, with obvious economic and environmental dimensions, while less obvious technological (e.g. automation of techniques), legal and marketing dimensions also contribute to its development. Several European laws, regulations and recommendations already consider seaweed-related activities in general, but updates may be necessary at various levels (e.g. for environmental protection and food safety). In addition, an emphasis needs to be placed on the correlations and links between different regulations and legislations related to seaweed and food safety. The visibility of clear-cut, transparent, coherent governance across Europe will help the development of the industry.

Finally, even if the market for food is often trend-based, Western consumers must be educated and incited to consider seaweed as food. Sensory-evaluation panels have been successfully implemented at the national/regional level and merit further development. It is recommended that a vocabulary be created to describe the flavour of seaweeds, so helping consumers to identify what they are buying, and what seaweeds add to their food, in terms of taste or nutrients.

Figure 25 highlights some of the bottlenecks identified in these guidelines.

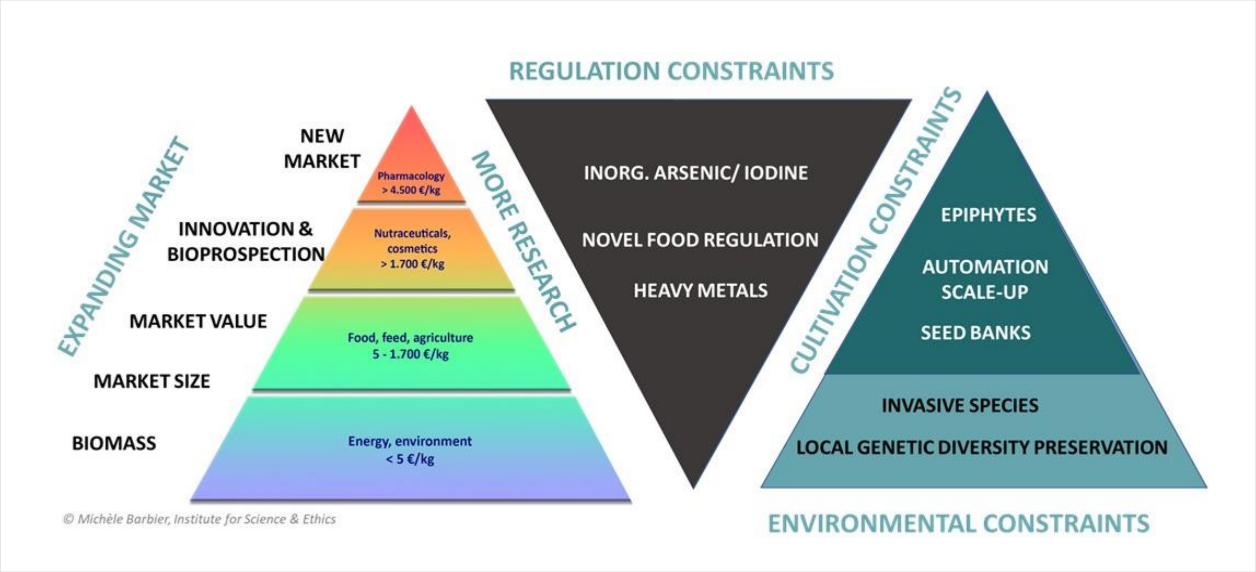

Fig. 25: The development of sustainable seaweed aquaculture in Europe comes across various challenges: market size, environmental constraints and the preservation of local genetic diversity, the need for more research – both fundamental and applied –, regulations on food quality, heavy metals or alien species, and cultivation constraints ranging from automation to epiphyte issues (© Michèle Barbier, Institute for Science & Ethics).

The main recommendations detailed in the various chapters of these guidelines are summarised below using a transversal and horizontal approach.

I - REMEDIATION ROLE

Seaweed can act as a mean for coastal protection and they role in flood defense should be further studied and understood. By their capacity in absorbing N, P and C, their potential role in ocean acidification and bioremediation at sea should be investigated *(see Chapter I on seaweeds as an opportunity to meet human needs).*

II - MARKET DIMENSION

To support the development of the seaweed industry, a market analysis is necessary at the European level to gain better knowledge of the market demand and structure in order to clearly identify the different uses of seaweeds in various sectors. Such study would guide seaweed farmers in the selection and diversification of their products. For existing farms, the innovative use of seaweed biomass can maximise its value, via the extraction of as many compounds as possible for different markets. The market for food and feed needs to be expanded and consumer education would accordingly help encourage the consumption of more and better quality seaweed products (see *Chapter II on Economic importance of seaweeds).*

III - EUROPEAN PRODUCTION

A better knowledge of current production yields at the European level is necessary and requires reference to homogenised measurements in biomass production, for measurement outcomes are variable, being for example directly dependent on the season, species, age, organs, drying methods used.

At the national levels, seaweed-aquaculture licensing procedures need to be simplified for greater transparency and efficiency while the social acceptability of seaweed concessions should be promoted. Moreover, it is important for all stakeholders and the whole industry (from policy makers, local authorities, researchers to the production sectors) to have trained personnel, thus requiring the development of training programmes in regional and/or national centres. Figure 26 sums up some of these needs (see *Chapter II on Economic importance of seaweeds and Chapter V on Challenges in market economy and regulation, section National aquaculture regulations and strategic plans).*

Fig. 26: To improve the market, many aspects must be taken into consideration (© Michele Barbier, Institute for Science & Ethics).

IV - CULTIVATION OF SEAWEED

IV.1. Cultivation at sea

The choice of the cultivated species depends on the trait of interest it presents to a pre-identified market, and on the cultivation site which has been selected for its environmental conditions. The geographic sites, the trait of interest and the species must all be congruent - a requirement that suggests local native species are the best suited, being well adapted to the given local environment (Figure 27). Regarding use of non-native species chosen for a specific trait of interest, studies should be carried out first to assess the potential impact of its introduction into the environment and its respective economic importance *(see Chapter III on Seaweed production and cultivation, and Chapter IV on challenges in the cultivation process).*

IV.1.1 Aquatic and marine-environment water quality

Aquaculture activities not only have the potential to affect surrounding communities but also to improve the quality of the water. These aspects should be adequately documented and considered when planning the locations of aquaculture facilities. The potential impact of the cultivated species on the local community should also be assessed. It is essential to preserve local genetic diversity; therefore, any reproduction events and/or dispersal from farms to the wild populations should be carefully monitored and prevented.

IV.1.2. Choice of species

To help farmers, maps of seaweeds available along the European coasts can provide tools to characterise the resources in the vicinity of each potential farm. For at-sea cultivation, the identification of local algal species will be useful for sourcing. To this end, a better knowledge of populations and their connections (i.e. level of gene flow) is needed to identify the optimal sourcing areas from which farmers can harvest fertile individuals and then produce “local strains”. In addition, the domestication process requires more research on the biology of seaweeds as well as the diversity of associated organisms (symbionts, pests, diseases), the structure of the marine ecosystem, and the evolution of human needs.
Definition of local geographic areas/limits for these local strains will also be helpful for authorising or prohibiting the transfer of strains from one area to another. Figure 27 sums up some actions to promote the preservation of European marine biodiversity *(see Chapter III on Seaweed production and cultivation, and Chapter IV on challenges in the cultivation process, sections Sourcing and Chapter VII on Research programmes to support sustainable development of seaweed aquaculture, section Biological and ecological challenges).*

Design: Michèle Barbier, Institute for Science & Ethics on Freepik

Fig. 27: Actions promoting the preservation of European marine biodiversity (Design: Michèle Barbier, Institute for Science & Ethics and Freepik)

As recommended, only native species should be cultivated at sea until population dynamics, and population genetics are better understood for each cultivated species. The use of non-indigenous species (specifically those imported from outside Europe) should be prohibited in the open sea unless control over the dispersion of these non-native species is implemented. For these organisms are potentially invasive, and if not, they can also act as vectors of introduction for new pathogens or pest organisms. In this way, understanding of pests and diseases nature and propagation must be increased to develop better management of resources. Toxic elements can affect human health either directly or indirectly by their accumulation in other organisms used for human consumption. Additionally, the fact that under the Marine Strategy Framework Directive only newly introduced non-indigenous species are a primary criteria potentially controls less the impacts of established non indigenous species (secondary criteria in MSFD). The dynamics of these species needs also to be assessed *(see Chapter IV on challenges in the cultivation process, section Recommendations and Chapter VII on Research programmes to support sustainable development of seaweed aquaculture, section Environmental impact of seaweed aquaculture).*

Regarding the management of non-native seaweed species in land-based aquaculture facilities, it is recommended that the Regulation (EU) 1143/2014 aiming to list all invasive alien species of Union concern (the Union list) be followed. If alien species are assessed as risky, measures (referring to EU Regulation 708/2007 on the aquaculture of alien species) should be deployed to prevent release and spreading in the open sea of land-based cultivated alien species. Currently the Union list does not include any marine species although the national lists of invasive alien species of Member States concern does include seaweed species. Given the open nature of the marine environment, the harmonization of lists between Member States should be promoted *(see Chapter V on Challenges in market economy and regulations).*

Photo credit by Shane Stagner from Unsplash

IV.2. Cultivation on land

In land-based systems, non-native species can be cultivated within a well-defined framework whereby the cultivation system ensures optimal treatment of discharged water to avoid any dispersal into the wild marine ecosystem. Such a system is likely to require the implementation of monitoring tools (methodology, applications and devices) and quality-control supervision of inlet and outlet waters (e.g. sterilisation of outlet water to neutralise spores). The use of alien species needs to be considered carefully *(see Chapter III on Seaweed production and cultivation, section Cultivation techniques).*

IV.3. IMTA

IMTA is a promising co-cultivation system but its development requires further research to optimise the technique. A framework should be set up for guiding the spatial organisation of open-sea aquaculture so as to maximise production (e.g. through the selection of optimal sites) while minimising impacts on the environment; this framework could be an integral part of local Maritime Spatial Planning *(see Chapter III on Seaweed production and cultivation, sections Cultivation techniques).*

IV.4. Selection programmes

When strains are chosen for their traits of interest, increasing their yield as well as their robustness is important. Well-planned and -designed breeding and selection programmes will help to achieve the goal of long-term sustainability but require further research to determine the appropriate conditions for cultivation given the high risk of dispersion of genetic materials escaping into the wild. In order to allow the "at-sea" producers to improve their own genetic resources and remain durably competitive, it is also important to focus selection programmes on the local wild resources *(see Chapter IV on challenges in the cultivation process, section Recommendations).*

IV.5. Preservation techniques

Once a strain with the specific traits of interest is successfully cultivated at one site, its maintenance and preservation are necessary. Indeed, climate changes, disease and pests may well decimate a population (as well as affect the local surrounding environment), as has already occurred in the past in Asia.
Preservation methods such as cryopreservation must be further investigated to ensure the maintenance of strains bearing the specific trait of interest *(see Chapter III on Seaweed production and cultivation, section Product processing and market supply).*

IV.6 Biobanks at regional technical centres

In parallel, the concept of biobanks (i.e. collections of strains from wild and cultivated populations) can provide a solution for ensuring access to interesting strains. It is advisable that each country develop infrastructures to breed and produce seedlings in nurseries for producers. Along European coasts, the biodiversity and the environmental conditions are quite different in the north compared to the south, in the Atlantic Ocean, the Mediterranean Sea, the North or Baltic Seas. Each European country should, therefore, set up agencies to collect and maintain stocks at the regional level, if this is in line with national strategy. These agencies could also contribute to state sovereignty over natural resources (Nagoya Protocol). Ideally, these agencies or technical reference centres would manage the collections of strains, provide producers with locally adapted seeds and listings of local seedling suppliers on request, and offer information and advice to facilitate collaborations among experts and farmers. These centres should also receive local elected officials, as well as professional representatives from the legal, financial (banking) and insurance sectors. This industrial-relations service would support the development of this sector by creating jobs at a regional level – although the sector still requires investment and social acceptability. These centres should be co-designed by professional experts.

A transparent database listing these regional/national entities would ensure access to technical information for producers and decision-makers alike for each country/region. Best practices drafted at the European level would benefit from coordination through these agencies *(see Chapter IV on challenges in the cultivation process, section recommendations).*

IV.7. National integrated governance

Taking the governance process further, an integrated system at the national level should gather experts from technical centres, research institutions and producers, to foster collaborations. This national-level system would provide support to producers by helping them to obtain financing for investment purposes or to cover damages in the event of vandalism, accidents or natural disasters *(see Chapter IV on challenges in the cultivation process, section recommendations).*

IV.8. Traceability and control of origins

The notion of local strains for a specific market - also usable as a marketing argument - requires appellations of controlled origin. The implementation of tools to ensure the traceability of all cultivated strains (indicators and procedures) is necessary. In particular, the indicators need to be homogenised across EU Member States. Certification procedures need to be impleASmented or transferred to existing certification centres for aquaculture such as the Aquaculture Stewardship Council *(see Chapter III on Seaweed production and cultivation, section Aquaculture management).*

IV.9. Cultivation techniques

In Europe, seaweed cultivation is still in its infancy but scientific knowledge on seaweed genetics is already available. To support the cultivation process, a better understanding of species' life cycles is also necessary. This knowledge would help to identify the technical factors that can control seaweed reproduction and growth. To protect local genetic diversity, assessment of the impact on local biodiversity should be undertaken before any launch of activity in the open sea. In addition, for the improvement of cultivated species, controlled breeding and selection programmes are needed.
The mechanisation of infrastructures or the automated harvesting of seaweeds cultivated offshore can help producers to scale up and reach the targeted production yields.
In general, more research is required to meet some of the challenges identified in seaweed production (Tables 13 and 14) *(see Chapter III on Seaweed production and cultivation, section cultivation techniques and Chapter VII on Research programmes to support sustainable development of seaweed aquaculture, section Environmental impact of seaweed aquaculture).*

Non-intensive strategies are recommended in at-sea systems and require prior definition of the "limits" of intensive cultivation. Alternative solutions consist in the combination of strains, alternation of species, spatial and/or temporal heterogeneity of cultivation practices. High densities in cultivation systems can prevent the presence of competing species but may increase the spread of pathogens in the farmed seaweed. Optimal densities must be adapted to each species. Strains and techniques can be improved at the local scale *(see Chapter III on Seaweed production and cultivation, section Cultivation techniques).*

Table 13: Identified research programmes to provide more understanding of the biology of seaweeds *(see Chapter VII on Research programmes to support sustainable development of seaweed aquaculture, section Biological and ecological challenges).*

	Challenges	**More research to**
Biology of Seaweeds	Conservation of species of interest	Develop cryopreservation methods
	Improve strains of interest through breeding and selection programmes	Understand the genetic compatibility and genomes interactions
	Cultivation of new species under artificial conditions	Understand the parameters that control fertility & reproduction
	Improve production of juvenile seaweeds	
	Improve the shape, texture and contents of seaweeds	Understand the impact of environmental factors (biotic and abiotic) on phenotypic traits of interest
	Prevent epiphytes, diseases and pests' blooms	

IV.9.1. Seasonal and geographic variability

Determining how long it takes for an operation to become profitable requires a better understanding of the number of years of cultivation that need to be invested before financial benefits are reaped. The influence of environmental factors such as temperature, nutrients, salinity and light also need to be known to identify optimal conditions for growth, biochemical composition or flavour per unit of time, effort and cost. Since the form and beneficial constituents of the one species can vary according to seasons and geographical regions, attention should be paid to the temporal and geographical distribution of characteristics of interest (either the extent of this variation, or the means to control or predict the characteristics of what is considered to be economically essential algae) *(see Chapter IV on challenges in the cultivation process, section recommendations and Chapter VII on Research programmes to support sustainable development of seaweed aquaculture, section Technical sciences and biotechnologies).*

IV.9.2. Pre-treatments

Relevant pre-treatment steps associated with efficient production systems are necessary to stabilise post-harvest seaweed biomass and ensure high-quality products that can undergo further conversion processes. More studies are required to develop these pre-treatment steps.

Conservation techniques (freezing, drying, fermentation) and alternative techniques require more research, and regardless of the technique used, their impact on the quality of the end-products as well as on the environment must be assessed. Product quality and safety should be quantified and, if possible, optimised, while energy efficiency must be improved *(see Chapter III on Seaweed production and cultivation, section product processing and market supply and Chapter VII on Research programmes* *to support sustainable development of seaweed aquaculture, section Technical sciences and biotechnologies).*

IV.9.3. Stabilisation process

Efficient stabilisation alternatives and optimal procedures to prepare biomass for production-chain extraction of high-value components will ensure access to seaweed biomass year round and support the growing demand for bioactive substances. The development of these procedures will create value in the coastal industry and support the sustainable development of the European bioeconomy based on the cultivation and processing of seaweed biomass *(see Chapter III on Seaweed production and cultivation, section Sourcing)*

Table 14: Research programmes necessary for improving cultivation.

	Challenges	**More research to**
Cultivation process	Impact on the environment	Control genetic dispersion
	Improvement of production	Optimization of facilities and technical itineraries
	New cultivation system such as IMTA	Optimize site location, co-cultivation best practices
	New cultivation artificial substrates	Develop an understanding of adhesion mechanism & adapt
	Biorefineries	Improve technologies & methodologies

V - SEAWEEDS AS FOOD IN LEGISLATION

The market for food is promising, even in Western countries, but a number of existing bottlenecks in legislation can hamper market development. An updated and complete list of seaweed species authorised as food in Europe should be compiled. Such a list would facilitate the work of seaweed companies wishing to introduce new products to the market, by determining the adequacy of regulations with the reality of the seaweed sector and contributing to food-safety control. The monitoring of heavy metals, iodine, arsenic etc. in seaweeds - an issue that is highly relevant to the market - can remove market barriers and provide clear updated signals/regulation on the threshold values of different contaminants. EFSA (European Food Safety Authority) is in the process of drawing up this list.

Additionally, the dissemination of this list of species authorised as food would increase public awareness of the use of seaweeds as food, for unfamiliarity currently stands as one of the main hindrances to the commercialisation of seaweeds as mainstream food products. Scientific proof is needed for risk-benefit analyses that take pros and cons into consideration. To back up claims that seaweed is a nutraceutical, bioactive food, or superfood, more research and clinical proof are needed (Table 15) *(see Chapter VI on Challenges in Food safety and Chapter VII on Research programmes to support sustainable development of seaweed aquaculture, section Food security and medical concern).*

V.1 Nutritional value

Although seaweed products are being developed rapidly, knowledge remains limited regarding the effects of preservation on the quality of seaweed biomass. General studies are furthermore needed on red, green and brown seaweed to evaluate the long-term effects of drying treatments, while alternative treatment solutions should also be investigated. The methods for determining some of the nutritional properties of algae are to be recommended by CEN/TC 454 Algae and Algae Products standardisation *(see Chapter VI on Challenges in Food safety, section Quality patterns).*

V.2 Compounds from seaweeds

New compounds extracted from seaweed should be checked for their eligibility as food ingredients according to the Commission Implementing Regulation (EU) 2017/2470; if they are unlisted, applications should be made for their acceptance. In parallel, species must be clearly and specifically identified to guarantee the sources of compounds extracted for the market. It is essential that the ongoing work on standardisation of identification methodologies carried out by the CEN/TC 454 be supported and encouraged *(see Chapter VI on Challenges in Food safety, section Recommendations).*

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V.3 Novel foods list

For the European Commission's (online) Novel Food Catalogue, a clear and rational overview should be developed to include an updated list of novel and non-novel (species already consumed as food before 15 May 1997) food products. To avoid misinterpretation of the online version content the designation should be changed to Food catalogue since it includes both novel and non novel food items. Currently novel food items (such as fucoidan extract from *Undaria pinnatifida* and *Fucus vesiculosus*) are not included on the online version of the novel food catalogue thus the online list should be updated. Also, an official list of all seaweed species accepted as food before 15 May 1997 should be compiled (possibly including notes on specific species accepted in different Member States), so that producers, companies and other stakeholders can consult an updated list, promoting a simplification of procedures.

Some seaweeds used in Europe, and thus already on the market, may not yet be approved as food (novel or non-novel), and are, therefore, not listed anywhere. These seaweeds should go through the authorisation process for novel food. Otherwise, they should not be on the market.

Some seaweeds used in Europe, and thus already on the market, may not yet be approved as food (novel or non-novel), and are, therefore, not listed anywhere. These seaweeds should go through the authorisation process for novel food. Otherwise, they should not be on the market *(see Chapter VI on Challenges in Food safety, section on List of edible species).*

V.4 Legislation on seaweeds as a safe food

Legislation on contaminants such as heavy metals and the problematic issues of iodine and inorganic arsenic should address seaweed "as food" and not "as food supplements" as is the case in the present legislative texts. Such legislation should also clearly state if threshold values are given in terms of the fresh or dry weight. A monitoring programme has been initiated at EFSA to compile analyses and evaluate threshold values for seaweed as food. Ideally, EFSA and the Novel Food Catalogue team should harmonise the list of seaweed species for food *(see Chapter VI on Challenges in Food safety, section Sources of potential contamination).*

V.4.1. Arsenic

The total arsenic threshold value is at present a market barrier. Feed legislation needs to be updated as does legislation on seaweed as food. As it is now possible to distinguish harmful inorganic arsenic from organic arsenic, the focus should be on providing the inorganic-arsenic threshold level rather than continuing to follow the outdated approach of giving the total-arsenic (organic and inorganic) level, as required by current feed legislation. Threshold values should also be specified as being on a dried- or wet-weight basis *(see Chapter VI on Challenges in Food safety, section Sources of potential contamination).*

V.1.2. Iodine

The high concentrations of iodine accumulated in some of the large brown seaweeds are market barriers. More knowledge is recommended on speciation/chemical form and bioavailability/uptake of seaweed iodine just as the development and dissemination of iodine-reduction methods are required. More generally, new methods for the detection of different chemical forms should be developed *(see Chapter VI on Challenges in Food safety, section Sources of potential contamination).*

V.1.3. Healthy food

Risk-benefit analyses including chemical risk assessments are needed to evaluate the health risks related to seaweed consumption. Research on high iodine content, heavy metals, nutrient or even nutraceutical effects of seaweed must continue for the purposes of ensuring food safety. There is a need for general risk-benefit analyses of seaweed with clear guidelines on which element under which form is beneficial/risky, at what levels (daily or monthly intake?), and which chemical form is present in the seaweed. The current EFSA work on monitoring seaweeds is timely *(see Chapter VI on Challenges in Food safety, section Sources of potential contamination).*

V.1.4. Organic certification

Organic certification exists for cultivated and natural populations of seaweeds, but it is overseen by a wide range of bodies while various certification processes apply in the different European countries. It is probably not feasible to set up a single organic certification process with harmonised regulations across Europe. However, best practices at the European level could guide, advise and homogenise the process across Europe *(see Chapter VI on Challenges in Food safety, section Standardisation and certification).*

V.5 Preservation of seaweeds for food

At present no specific legislation exists on quality stability (e.g. is a seaweed product still safe for consumption after two months?). There is a need for increased knowledge about the impacts of post-harvest handling (e.g. preservation treatments) on the quality and quality stability of seaweed (nutrient content, organoleptic properties) destined for food applications (food safety). Best storage procedures/industrial-classification codes including self-checks must be determined for each species and product along with best practices for the evaluation of product shelf-life. Further research is needed to: *(i)* minimise losses of valuable compounds; *(ii)* ensure product safety; and *(iii)* limit the energy consumption and associated costs. This is a key to increasing the industry's profitability *(see Chapter VI on Challenges in Food safety, section Quality patterns).*

Moreover, for preservation/downstream processing, industrial-classification codes should be drafted by producer companies in collaboration with food authorities. These codes can also be drawn up in collaboration within EU seaweed experts for the purposes of establishing common rules.

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The development of the food market for seaweeds is ongoing. However, bottlenecks that hamper the market development have been identified in European legislation. Integrated European governance stands to benefit from the recommendations listed above. In parallel, additional research is needed to provide greater understanding on how to secure seaweeds as food, as reported in Table 15 *(see Chapter VI on Challenges in Food safety, section Recommendations).*

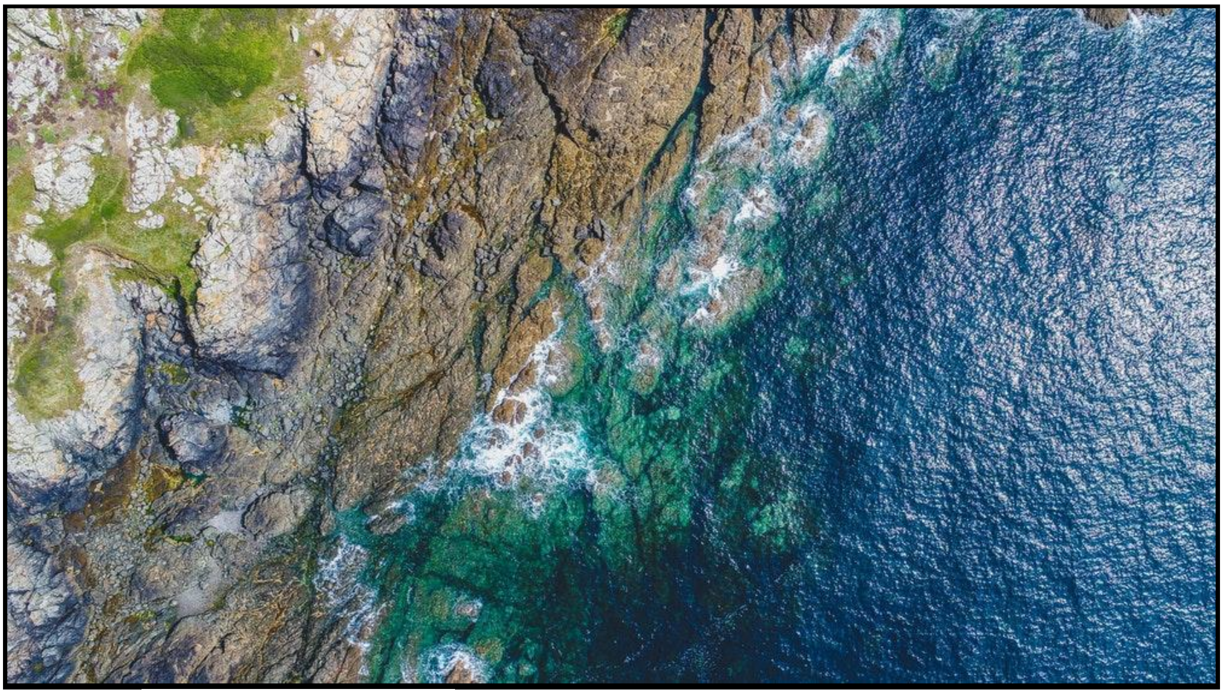
Table 15: Recommendations (for policy makers and researchers) for fostering development of the market for seaweeds as food.

Challenges and needs for the Industry	**Recommendations**	
	Research	**Governance**
Secure food security: inorganic arsenic, iodine, heavy metals	Risk-benefit analyses and more knowledge on speciation of iodine/chemical form, bioavailability	Update the threshold value of contaminants and define this for seaweed as food, and a common standard: on dry weight or wet weight basis
Elevated concentrations of iodine in some large brown seaweeds, Surveillance of potentially undesirable compounds in edible seaweeds	Standardization & definitions of chemical compound classes, activities, traceability, methods and species identification	Surveillance of undesirable compounds and definition of related norms
Food preservation to maintain persistent contents and increase organoleptic properties	More knowledge on preservation methods & treatments on the biomass	Implement certification centres.
Impacts of post-harvest handling (preservation treatments) on the quality and quality of the stability of seaweed (nutrient content, organoleptic properties), need stabilization of seaweed biomass	Definition of best storage procedures & best practices to evaluate product shelf-life	Implement best practice/industrial classification codes developed in collaboration with companies and national/European authorities
Various certification processes for organic certification in the different countries of the EU.		Homogenise organic certification across EU
Know more on seaweed impact in the human body and effect on health	Risk- benefits analyses of seaweeds	Identify the limits for consumption (e.g. on a daily basis)
Cultivate additional seaweed	More knowledge on the domestication process	
Attract consumers	Implement sensory evaluation panels	Increase public awareness, define a vocabulary to describe the flavour of seaweed

To boost the sustainable development of seaweed aquaculture in Europe, these guidelines call for the harmonisation of legislation and management frameworks across Europe on exotic species, cultivation rules, environmental protection, evaluation of the risk of loss of wild biodiversity, marine-water quality and the cultivation of hybrids.

The scientific community must anticipate needs and develop knowledge on the biology of marine macroalgae, namely seaweed growth, reproduction, physiology, metabolism, pathology, ecology, and the environmental impact of their cultivation.

A clear understanding of current production in Europe is also needed, including standardisation of biomass production and quality assessment.



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AFTERWORDS

PEGASUS was released in May 2019.

It was prepared by 50 contributors from several countries worldwide.

During the previous 18 months, PEGASUS outlines and preliminary versions were presented in different international conferences and to several groups of European stakeholders.

PEGASUS was open to an international public consultation in December 2018.

PEGASUS was presented at the European Parliament in February 2019, upon an invitation from the Searica intergroup (Seas, Rivers, Islands, Costal Areas integroup).


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EUROPEAN COOPERATION
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