



Development and objectives of the PHYCOMORPH European Guidelines for the Sustainable Aquaculture of Seaweeds (PEGASUS)

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Review

Michèle Barbier*, Rita Araújo, Céline Rebours, Bertrand Jacquemin, Susan L. Holdt and Bénédicte Charrier

Development and objectives of the PHYCOMORPH European Guidelines for the Sustainable Aquaculture of Seaweeds (PEGASUS)

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Abstract: Seaweed resources play an increasingly important role in European Blue Growth and Bioeconomy strategies and European production is anticipated to increase dramatically with the continued up-swing of global market interests in seaweed resources. As a consequence, there is a need to ensure the environmental sustainability of future aquaculture activities, as reported in the PEGASUS white paper. The present article summarizes the published PEGASUS guidelines developed in the framework of the COST Action Phycomorph, for the future development of this sector. This includes the advances made in this important arena of applied phycology taking into account scientific, technical, environmental, legal and socioeconomic dimensions. Challenges, bottlenecks and risks are identified and presented with a special focus on production issues regarding productivity, breeding, choice of appropriate cultivars, disease and pests and also the risk of using non-indigenous and invasive species as candidates for cultivation. The barriers for long-term, sustainable exploitation are also examined including harmony with the European “Nutrition and Health Regulations”

necessary in order to ensure food safety. The PEGASUS guidelines provide scientific recommendations required to address the above issues and to provide science-based advice to policymakers, managers and industries for the sustainable development of industrial-scale seaweed aquaculture in Europe and beyond.

Keywords: aquaculture; ethics; food safety; genetics; legislation; research programs; sustainable.

Introduction

The domestication of marine species is widely considered as a possible solution to increase food and could be one of the most important future developments in human history. By 2050, the biomass of edible bio-resources will have to satisfy the 10 billion people who would live on the planet (Ranganathan et al. 2018, O’Shea et al. 2019).

Seaweeds, which play a key ecological role in coastal ecosystems (i.e. foundational), are used for a variety of applications. Their cultivation, through the aquaculture industry, can help address global challenges related not only to consumption but also to human health, agriculture, coastal issues management and contribute to a sustainable circular bioeconomy and blue growth.

Interest in the many industrial applications of seaweed biomass continues to grow supporting a yearly production of 31 million tonnes with a total estimated value of about €10 billion (annual growth of about 6%) (FAO 2016, Buschman et al. 2017). Seaweeds are therefore a promising bioresource for the future and the demand for high value-added derived compounds for cosmetics or food is increasing in Europe. However, the total European production represents less than 1% of world production (Camia et al. 2018). To increase this European production, the seaweed aquaculture sector requires additional investment in research and development and the European industries involved in the development of

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sustainable seaweed aquaculture should be supported. However, as there is currently no specific legislation or directive regulating this developing sector (which lies under the general aquaculture regulatory framework that might not adequately address the specificities of the seaweed sector), the potential risk of environmental impact should not be overlooked. It is therefore essential that scientific advances and knowledge about seaweeds (from their biology to the gene-flow process in the environment) be embraced by industry and policymakers.

In order to transfer this very specific and advanced knowledge, a group of expert scientists have joined forces to provide advice to the actors of this sector. As part of the Phycomorph COST Action, they published guidelines entitled “Phycomorph European Guidelines for a Sustainable Aquaculture of Seaweeds – PEGASUS” (Barbier et al. 2019). The aims of the guidelines are:

- (a) to promote this sector and anticipate potential risks with solutions and recommendations to avoid a bad management of the sector.
- (b) to support and stimulate the economic development of this sector.

This work reviewed the specific related scientific knowledge as well as the existing legislation in order to identify, discuss and recommend possible solutions to the bottlenecks hindering the development of seaweed aquaculture in a bioeconomic context. The present paper is the summary of the full white paper report PEGASUS. PEGASUS was also presented to various stakeholders across the world and in particular to the European Parliament (February 26, 2019) to bring awareness to

policymakers about the strength and weakness of this emerging industry and the need for appropriate governance frameworks to both facilitate and control its sustainable establishment in Europe.

Seaweed aquaculture in Europe: context and identification of challenges

Ecological and economic importance of seaweeds

Seaweeds play a key ecological role in coastal ecosystems, providing habitat for other marine species, protection to coastal communities, bioremediation by removing nutrients in excess and acting as a reservoir for CO₂. The potential of seaweeds for ecosystem management, the production of bioplastics and as feedstock for biofuel production is also being explored. Seaweeds can also be used for a variety of applications: as raw materials for food and nutraceuticals, well-being and cosmetics, animal feed and fertilizers.

Seaweed aquaculture can help address global challenges related to human consumption, health, aquaculture development and management, and the sustainable circular bioeconomy (EC 2018) and blue growth (Figure 1). Additionally, seaweed aquaculture is relevant to the sustainable development objectives of the United Nations by addressing several of its goals (no poverty, zero hunger, gender equality, decent work and economic growth,

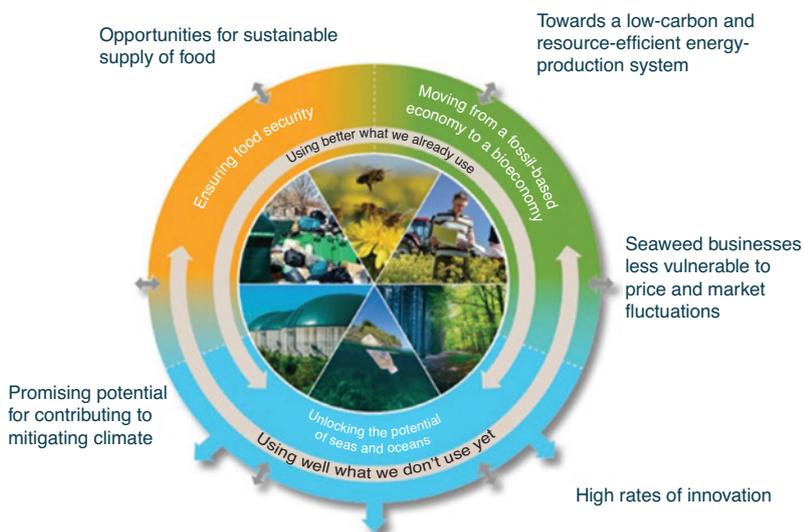


Figure 1: Seaweed aquaculture to meet the goals of the European bioeconomy strategy (© Michele Barbier, based on EC documentation, 2018, source photos: iStock, © roxyminder #94394792; Fotolia_110024322_Subscription_XXL_© Countrypixel.jpg).

industry, innovation and infrastructure, responsible consumption and production, climate action and life below water). In order to meet the growing food security challenge, aquaculture and thereby also seaweeds need to be part of the solution to support the future supply of healthy protein to the world in a responsible and environmentally friendly way (O'Shea et al. 2019).

The main producers of seaweed biomass are Asian countries, China, Korea, the Philippines, and Indonesia, which supply 97% of the global seaweed biomass (FAO 2019). The production status in North America and Chile, as well as the initiatives launched in Africa, are briefly presented in the guidelines. European production, which is still mainly based on the harvesting of seaweeds, aims to develop seaweed farming in line with the economic and societal strategies and priorities of the various European countries. Data on seaweed production in the various European countries are insufficient to understand the current dimension of the sector, but European aquaculture started in 1985 and now stands at 1755 tonnes with a value of US\$ 377,2000 (FAO 2019). The main cultivated species are the kelps *Saccharina latissima* and *Alaria esculenta*, and the green macroalgae *Ulva* spp. On a smaller scale, the red seaweeds *Porphyra/Pyropia* spp. and *Palmaria palmata*, the green seaweed *Codium tomentosum*, and the kelp species *Laminaria digitata* are also cultivated. It is clear from this overview that a better understanding of current production in Europe is needed and should include the assessment of both biomass production quality and environmental impact of the whole value chain.

Challenges identified in the European landscape

Through the review of the current situation in Europe in terms of seaweed cultivation and production, food safety and legislation, and details on the status of development in the main producing countries, challenges were identified. Many of them arise from the different stages of seaweed cultivation, from the origin of the cultivars and the domestication of the species of interest to the development and optimization of the cultivation techniques up to the market supply. The most important measure to be undertaken is the necessary assessment of the potentially serious and often irreversible environmental impacts of seaweed aquaculture, prior to cultivation. This includes the physical impact of the cultivation facilities on the ecosystem, the introduction of alien species or genotypes, the risk of dissemination of parasites and pathogens to the wild populations and the preservation of the local biodiversity (Figure 2). The production of the best cultivar according to the market expectations is a second main challenge. Although several regulations and recommendations apply also to seaweeds currently, as reviewed in Figure 3, no specific European legislation exists regarding the aquaculture of seaweeds. 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). And an emphasis needs to be placed on the correlations and links between the different regulations and legislation related to seaweed and food safety. The

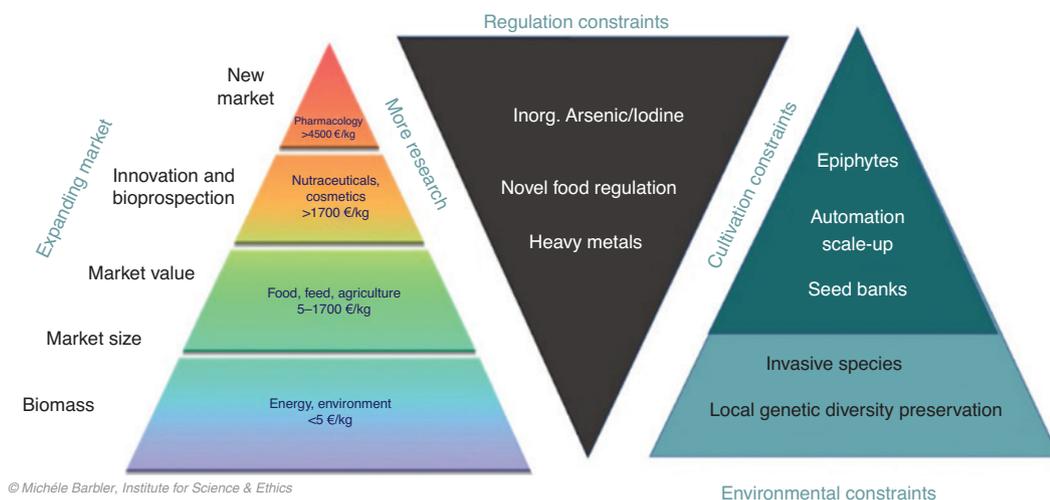


Figure 2: The development of sustainable seaweed aquaculture in Europe faces a number of challenges: market size, potential environmental impact, and preservation of local genetic diversity, the need to intensify research – both fundamental and applied, regulation of food quality, heavy metals or alien species, and cultivation constraints ranging from automation to issues of epiphytism (© Michele Barbier).

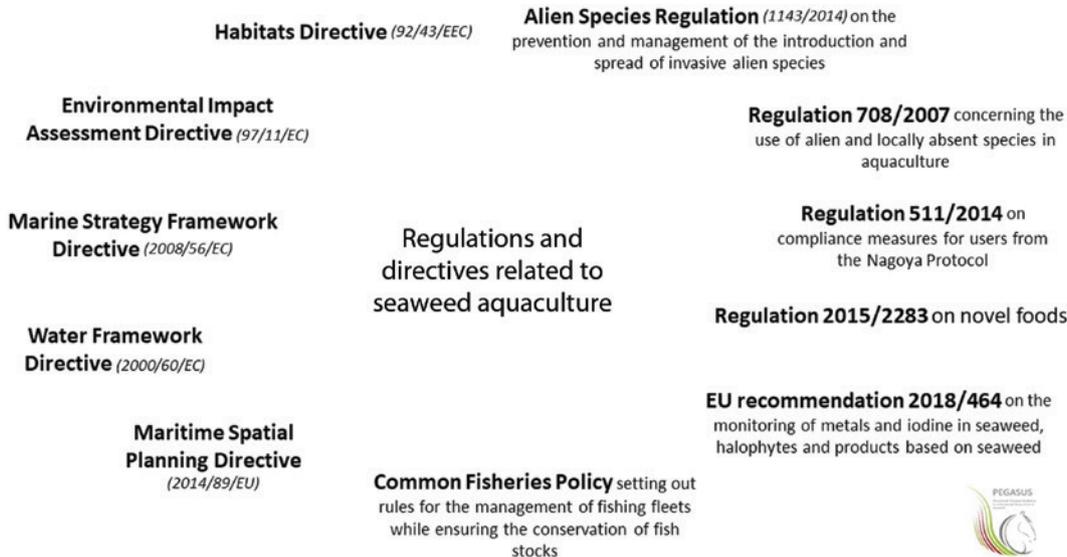


Figure 3: Different European legislation with implications for seaweed aquaculture (© Michele Barbier).

visibility of clear-cut, transparent, coherent governance across Europe will help foster the development of the industry.

PEGASUS emerged from the European network Phycomorph

COST action PHYCOMORPH FA1406

Considering that the potential of seaweed cultivation would be a determinant for the future of the European sustainable production of biomass, the European COST Association (www.cost.eu) funded a project involving a group of experts in seaweed growth and reproduction. Its mission was to build a network dedicated to (1) the advance of knowledge in seaweed biology, (2) capacity-building in the seaweed research community and training of early-stage scientists in macroalgal studies and cultivation, and (3) the preparation of guidelines for sustainable aquaculture of seaweeds in Europe. Over 4 years, the network Phycomorph (www.phycomorph.org) gathered more than 350 scientists of the public and private sectors from 20 European countries and eight additional ones from America, Asia and North Africa. The partnership deployed during the Action led to several oral or poster presentations during conferences (EPC6 London, IPC11 Szczecin) and to the publication of 28 collaborative articles, book chapters and books, among which is *Research Topics in Frontiers in Plant Science* (2015, open access: <https://www.frontiersin.org/research-topics/2598/>

from-the-emergence-of-multicellularity-to-complex-body-architectures-update-and-perspectives-on-the#overview). Notably a special issue of *Botanica Marina*, 2017, vol. 60, issue 2: Phycomorph: macroalgal development and morphogenesis, partly open access), which included reports of progress in the identification of the environmental and cellular (including bacteria) parameters controlling life cycle phase transitions and seaweed morphogenesis (Katsaros et al. 2017, Martins et al. 2017, Weiss et al. 2017) together with a new technique based on infra-red spectrometry to quantify carbohydrate in *Ulva* blades (Shefer et al. 2017). More methods developed recently on different aspects of macroalgal biology and cultivation were then published in the book *Protocols for macroalgae research* (Charrier et al. 2018).

In addition to publications, capacity-building through 25 short-term scientific missions strengthened bonds between COST members and promoted the development of new research topics. Sixty students acquired new skills in:

(i) seaweed cultivation, (ii) genomics and transcriptomics, (iii) analytical chemistry and (iv) microscopy and cell biology techniques, all focused on macroalgae, through Training Schools and Workshops organized during the past 4 years.

However, evidence quickly arose that the production sector was too tiny and fragile to be able to fully benefit from the European progress made in fundamental knowledge and cutting-edge techniques. Attempts to boost the transfer of academic knowledge to the farming sector was illustrated in a Phycomorph collaborative viewpoint paper (Charrier et al. 2017). However, for the sector to develop,

a broader scope of bottlenecks was to be identified, and then solutions proposed to pass them. Relying on the bonds established during the first 2 years, the network further expanded during the preparation of the guidelines. Experts in seaweed cultivation (fertility, production of juveniles in the hatchery, biomass production from field cultivation, disease, metabolism, genetics and domestication), exploitation (trait definition, biomass conservation, standardization, refinery), research (genetic improvement, cryopreservation, bioprospective) and ethics were contacted throughout the world.

PEGASUS methodology

For 18 months, six coordinators identified based on their complementary expertise, synthesized the contributions of 48 international experts from 20 different countries worldwide to draft the recommendations. In order to always involve a wider community, draft versions have been presented at various international conferences and to several European stakeholder groups: EU Aquaculture Advisory Council (May 2018), Aquaculture Canada 2018 conference, AQUA 2018 (World Aquaculture Society), Annual Scientific Conference of the International Council for the Exploration of the Sea (Sept 2018). PEGASUS was also opened for international public consultation in December 2018 to receive criticism and improve content accuracy and relevance for all stakeholders. Changes in the direction of progress have regularly been made based on feedback from the European Commission through the involvement of the EU Joint Research Center (which maintains an inventory of European seaweed cultivation companies and production methods). Updates were regularly presented to the DG-MARE (European Commission). The guidelines are divided into eight chapters:

Chapter I – Seaweeds as an opportunity to meet human needs; Chapter II – Economic importance of seaweeds; Chapter III – Seaweed production – Cultivation; Chapter IV – Challenges in the seaweed cultivation process; Chapter V – Challenges in market economy and regulation; Chapter VI – Challenges in food safety; Chapter VII – Research programmes to support sustainable development of seaweed aquaculture; Chapter VIII – Conclusion – Summary of recommendations for the sustainable development of seaweed aquaculture in Europe. It provides a multidimensional framework for the sustainable and profitable development of aquaculture. This 200-page document is open access (<http://phycomorph.org/pegasus-phycomorph-european-guidelines-for-a-sustainable-aquaculture-of-seaweeds>) together with a shorter

version reviewing the main recommendations and a flyer. These later documents were designed to ease the reading and understanding of the guidelines for policymakers, industries as well as society.

PEGASUS recommendations

PEGASUS performed both a thorough analysis of the current state of European production and identification of challenges and bottlenecks that currently prevent the development of the seaweed aquaculture sector in Europe, as summarized in the sections above. The aim is to contribute to the development of maritime economic activities while preserving the marine environment. It should be considered as a technical and scientific advice tool provided to all stakeholders.

Inter alia, PEGASUS provides specific details on the regulatory framework that currently applies to the production and consumption of seaweeds as food or food supplements. PEGASUS helps to reveal this multidimensional sector, which has noticeable economic, social and environmental dimensions, and less understandable technological, legal and marketing aspects that also contribute to its development. These guidelines are fully in line with the recommendations of the United Nations guidance document (Cottier-Cook et al. 2016). PEGASUS specifically aims to better understand the current situation in Europe in terms of seaweed cultivation and production, food safety and legislation, with details on the status of development in the main producing countries.

The guidelines also identified what research topics should be prioritized in the future to support the sustainable development of the seaweed industry. The main recommendations are summarized below.

Seaweed production and cultivation in Europe

The guidelines consequently recommend that the origins and characteristics of the cultivated species shall be well defined. This means a good identification of the genetic structure and distribution around the farms of the wild populations for the cultivated species. At sea, only local populations of native species should be cultivated until population dynamics and genetics are better understood for each species of interest. The import of species from outside Europe should be prohibited for sea cultivation or open systems and should be closely monitored for

confined terrestrial systems before the potential impact of its introduction in the local environment is assessed.

Mapping the biological material available along the European coasts would provide tools to characterize the resources in the vicinity of each potential farm for supply. Moreover, the transfer of strains from one area to another must be controlled to avoid gene flows between foreign and local populations. Therefore, it is necessary to define the geographical limits of what is meant by “local strains” and to prevent breeding events and/or dispersal from the cultivated to the wild populations.

Collections of strains of the cultivated populations and of the wild populations should be established. Such bio-banks would safeguard the conservation of wild genetic diversity, thereby ensuring future production. The preserved strains could then be used for breeding and selection programs. Additionally, technical structures such as hatcheries/nurseries for producers should be developed while putting in place tools to ensure the traceability of all crop strains (indicators and procedures). The guidelines extensively describe the urgent need to develop pest and disease control for marine or terrestrial systems. However, in order to do so, more research is needed to understand the processes of infection.

The guidelines emphasize the selection of traits of interest and how to improve the strains. Depending on the species and its reproduction mode, selection programs targeting the improvement of cultivated strains are basically based on either a clonal line, a single-parent line or a recombinant line, and the improvement in processes is detailed. Out-breeding or in-breeding techniques have different genetic impacts but both can lead to a decrease of the fitness (i.e. the capacity and strength of one individual to survive and to reproduce in order to produce a surviving and fertile offspring) for the cultivated population and/or a loss of genetic diversity in the wild populations (Jacquemin 2017).

Techniques for seaweed production (detailing their potential and challenges) are also presented and summarized in Table 1.

During the last two decades, Integrated Multi-trophic aquaculture (IMTA) has been proposed as an eco-friendly strategy for sustainable marine biomass aquaculture (Chopin 2006). However, more research is needed about how IMTA techniques can be developed in order to reach the environmental, economic and social benefits of such a strategy.

Cultivation techniques can also be improved, such as adhesion of offspring to artificial substrata. Progress on developing the biorefinery approach for the seaweed value chain is necessary.

Cultivation and seasonal and geographic variability

Before cultivating a new species, it is necessary to identify its market relevance and the traits of interest. Determining the time needed to make the farm profitable requires a good understanding of all the necessary investments.

The domestication of new species requires a good knowledge of its life cycle: the influence of environmental factors such as temperature, nutrients, salinity and light in the growth dynamics and biomass characteristics must be known to identify optimal growing conditions, biochemical composition or flavor and optimize cultivation effort and cost. Since the beneficial form and constituents of a species can vary according to geographic regions, attention should be paid to the temporal and geographical distribution of characteristics of interest.

The development of seaweed aquaculture involves, in the medium and long term, the expansion of cultivation areas. However, the environmental impact of offshore cultivation is not sufficiently known. Non-intensive farming strategies are recommended until more understanding of the environmental impact is reached. The guidelines call for the assessment of the potential impact of the cultivated species on the local community. Therefore, in order to preserve local genetic diversity, the guidelines recommend that any reproduction events and/or dispersal from farms to the wild populations should be monitored and means must be taken to prevent drastic modification of the biodiversity.

Industrial perspectives

The costs of harvesting, pre-treating and processing raw biomass influence the choice of scenario involving the production systems, both at sea and on land. All these aspects and specifically the choice of species with the desired characteristics (e.g. production of biomass to extract alginates, carrageenans or other compounds for cosmetology) must be considered before setting up a farm.

Mechanization of infrastructure or automated harvesting of seaweeds grown at sea can help producers increase and achieve targeted production yields. Reducing transport times and volumes is also one of the key aspects.

After harvesting, biomass stabilization processes are important. Efficient stabilization alternatives and optimal procedures for preparing biomass for the extraction of high-value components from the production chain will

Table 1: Techniques for production of various types of seaweeds.

Techniques	Advantages	Challenges	Measures
Harvesting from the wild populations	Based on traditional local economy	The exploitation of wild resources needs to be sustainable Compliance with Nagoya Protocol Manual status not recognized	Define limitations/ quota Management/harvesting plan when none existing
Free-floating Land-based monoculture	High yield and yearly cultivation Easy to harvest Controlled environment Unlimited number of species	Low scale of production Need space on land High infrastructure costs High operational costs	Use existing structures (ponds/raceways) Adapt actual landscape management plans Use renewable energy for light, temperature and water circulation
Sea-based monoculture	Low cost Can be 1D, 2D or 3D Open space	A limited number of authorized species Farm location (nutrients, natural conditions, environment) Risk of the escape of vegetative (propagules) or reproductive (gametes, eggs) materials Impact on local genetic diversity Disease/multiple pests	Research on the distribution of the species of interest Environmental condition monitoring Define geographical limits of the “local” area Balance in-breeding/out-breeding programme
Integrated multi-trophic aquaculture (IMTA)	Low nutrient requirements Shared infrastructures and distribution channels Shared investment and infrastructure Reach new consumers Eco-friendly production systems	Same as monoculture systems (see above) Find the optimal combinations of species (overlap of life cycles, functional groups...) Find the best location for different species (depth, freshwater, estuary) Risk of cross-disease and multiple pests	Definition of best practices More research needs to define best locations Modelling Collaboration with ongoing high-level trophic production sites such as salmon farms
Offshore	Space management Cost of infrastructure Investment for systems that can be deployed in the open sea	Same as monoculture and IMTA systems (see above) Regulation to manage the access and use of the resources beyond national jurisdiction Transport back to customers including logistics, costs and environmental footprint or processing factories	Definition of best practices Economic and environmental modelling to define potential scenarios and optimize space and infrastructure use Collaboration with the fisheries industry and maritime transport companies Collaboration with salmon farms developing activities in the open sea

ensure access to seaweed biomass all 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 bio-economy based on the cultivation and processing of seaweed biomass.

Integrated European governance should be implemented

For cultivation process, facilities, reference cooperative technical centers and certification consortium structures should be implemented. For the governance procedures, an integrated system at the national level should bring together experts from technical centers, research institutes, producers, and industries in order to foster

collaboration. This would provide support to producers by helping them to obtain funding for investment purposes or to cover damage in the event of vandalism, accidents or natural disasters. Technical reference centers should be set up with expertise to assist local farmers and/or identify suppliers on request at the regional level. The introduction of certification consortium structures for the control of the origin of strains grown at the national level should be considered, as well as the standardization of best practices for seaweed aquaculture across Europe.

The notion of local strains for a specific market requires registered designations of origin. The implementation of tools to ensure the traceability of all culture strains is necessary. In particular, the indicators (such as molecular DNA markers, values for the traits of interest, and some geographical information about the origin of the strain) must be standardized and harmonized across

the EU Member States. Certification procedures should be implemented or transferred to existing aquaculture certification centers.

Market economy and regulatory framework

EU-level regulations

Seaweed aquaculture activities must comply with the requirements of the European directives managing the protection and sustainable use of the marine environment (Figure 3).

The main challenges identified in relation to the development of seaweed aquaculture are related to the potential environmental impacts of the production facilities that still need to be adequately evaluated. These potential impacts might conflict with directives protecting, for example, marine biodiversity, managing the maritime space uses and optimization of production sites and supporting the development of an ecosystem-based approach for seaweed aquaculture. One particular concern is the use of alien or locally absent species in aquaculture. Better knowledge on the risk of these species to the environment is needed and better coordination across Europe to harmonize the national lists of invasive alien species of Member State concern is recommended. A list of alien species of economic interest in Europe should be established and their potential impact on the environment evaluated by risk assessment studies.

National aquaculture regulations

The guidelines provide detailed information, at the national level (Denmark, France, Ireland, Norway, Portugal, Scotland, Spain), on the development and main challenges of the seaweed aquaculture sector and seaweed aquaculture related regulations. As for the EU level, for most countries with the exception of a few very specific pieces of legislation, no regulation for seaweed aquaculture is in place and this activity follows the regulatory framework of the other aquaculture activities. The status of development of the sector is very country-specific. Some of the main challenges identified are related to the complex licensing processes, the need for more knowledge on species traits and environmental drivers and public acceptance of the aquaculture activity.

Market

Commercialization, consumer awareness and education, rules to import seaweeds or seaweed products into Europe, are all important issues because they are the suction force of all sectors. Random checks at the borders should be carried out on imported products as well as on domestic products which must comply with Community or National legislation on the different seaweed uses.

Food safety

The food market is promising, even in Western countries, but a number of existing bottlenecks in legislation can hinder market development with regard to providing safe food (e.g. authorized and non-contaminated food). This chapter provides an update on seaweed species, classified as novel food, food or not accepted as food (due to lack of application for authorization) according to the EU Novel Foods Catalogue (2018).

The requirement for a complete list of seaweed species authorized as food in Europe

Such a list would facilitate the work of companies in the seaweed sector wishing to introduce new products to the market and would contribute to the compliance with food safety requirements. In addition, the dissemination of this list of species authorized as food would increase public awareness of the use of seaweed as food, as their lack of awareness is currently one of the main obstacles to the marketing of seaweed as a common food product.

Legislation

Legislation on contaminants such as heavy metals and the problems posed by iodine and inorganic arsenic should cover seaweed “as food” and not only “as a food supplement” as is the case in the current legislation (EU recommendation 2018/464). Monitoring and evaluation of harmful components and update threshold values of heavy metals, iodine, arsenic in seaweed can remove trade barriers and provide clear and up-to-date guidelines on the adequate threshold values for different components and their effect on health when seaweeds are consumed. Organic certification exists for cultivated and natural

seaweed populations but is supervised by a wide range of organizations, while various certification processes apply in different European countries. Best practices at the European level could guide, advise and homogenize the process.

Consumption of various seaweeds: risk-benefit analyses

Some health benefits of seaweeds are demonstrated, but risk-benefit analyses (including chemical risk assessments: high iodine content, metals, and nutrients) should be performed. To support claims that seaweeds are a nutraceutical, bioactive food or superfood, complementary scientific research and clinical evidence are necessary. Clear information regarding the chemical form of the compounds, the amount and the intake frequency are required. The current work of the European Food Safety Authority (EFSA) on this topic is very timely.

Preservation of seaweeds for food

There is a need to increase knowledge about the effects of post-harvest handling – conservation treatments – on the quality and stability of marine macroalgae (nutrient content, organoleptic properties) for food applications. Best storage should be determined for each species and product, as well as best practices for improving and securing the shelf life of products.

Food market

For downstream preservation/processing, industrial classification codes should be drafted by the producing companies in collaboration with the food authorities. These codes can also be developed in collaboration with EU experts in seaweeds to establish common rules. Finally, although the food market is often trend-oriented, Western consumers need to be educated and

Table 2: Research programs to provide a greater understanding of the biology of seaweeds.

	Challenges	More research to
Biology of seaweeds	Conservation of species of interest Improve strains of interest through breeding and selection programs Cultivation of species new for aquaculture under artificial conditions Improve production of juvenile seaweeds Improve the shape, texture, and content of seaweeds	Develop cryopreservation methods Understand genetic compatibility and genome interactions Understand the parameters that control fertility and reproduction Understand the impact of environmental factors (biotic and abiotic) on phenotypic traits of interest

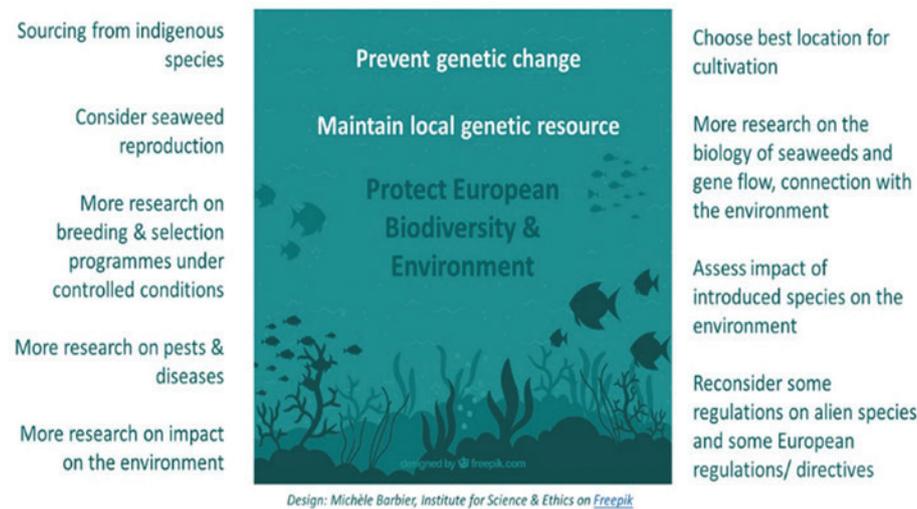


Figure 4: Actions promoting the preservation of European marine biodiversity (© Michele Barbier, source photo © freepick.com).

encouraged to consider seaweed as food. It is recommended to create a vocabulary to describe the flavor of seaweed, in order to guide consumers' choice, in terms of taste or nutrients.

Required research programs

Specific research programs should be supported to meet industrial needs for the bio-banking, domestication, cultivation, production and safe consumption of

seaweed, as well as prospective research for new products. Algal cultivation in Europe is still in its infancy, but a significant amount of scientific knowledge on the genetics of marine algae is already available. A better understanding of the life cycle of species resistant to cultivation would identify the technical factors enabling the control of the reproduction and growth of additional seaweeds of economic interest (Table 2). In addition, controlled selection programs should be deployed to produce domesticated seaweeds as genetically close as possible to the local wild population and free from

Table 3: Selection of some challenges for the development of the seaweed industry sector with related recommendations for research and governance.

Challenges for the industry sector	Recommendations	
	Research	Governance
Secure food security Assessment of inorganic arsenic, iodine, heavy metals	Risk-benefit analyses and more knowledge on speciation of iodine/chemical form, bioavailability Definition of chemical compound classes Standardization of detection methods, activities, traceability, methods and species identification	Update the threshold value of contaminants and define this for seaweed as food, and agree on a standardized factor (dry weight or wet weight basis)
Food preservation to maintain persistent contents and organoleptic properties, and ensure shelf life and food safety	More knowledge on preservation methods and treatments on the biomass	Implement best practice/industrial classification codes developed in collaboration with companies and national/European authorities Implement certification centers
Various certification processes for organic certification in the different countries of the EU		Share best practices for organic certification across EU countries
Know more on seaweeds effect on health Secure cultivation of seaweed and allow cultivation of additional seaweed	Risk-benefits analyses of seaweeds More knowledge of domestication processes More knowledge on seaweed biology (growth, development and reproduction) More knowledge of seaweed diseases	Support research through funding programs
Attract consumers	Implement sensory evaluation panels	Increase public awareness, define a vocabulary to describe the flavor of seaweed
Compliance with EU and national guidelines on the protection of the marine environment	The potential impacts (positive and negative) of seaweed aquaculture in the environment need to be better documented The risk and impacts of the introduction of non-native species need to be assessed	Avoid the introduction or expansion of cultivation sites of non-native species until their potential impacts are known
Optimize cultivation in IMTA systems	Optimize species combination and cultivation techniques	Adapt the existing regulatory framework from each sector (fish, mollusc, etc.)
Planning usage of maritime space to implement "at sea" cultivation facilities	Integration of seaweed cultivation in the existing usage of the maritime space Coordination of the temporal and spatial organization of these activities. Such structuring should be regularly updated according to the evolution of the different sectors	
Social acceptability	Societal education	A commitment of the civil society in decision-making processes regarding maritime space uses

the risks of in-breeding and out-breeding in order to preserve the local biodiversity together with the maintenance of the selected traits of interest (Figure 4). More effort invested in seaweed biorefinery should allow the identification of new integrated processes and protocols enabling cost-effective improvement of e.g. energy production, food/protein supply and water quality. However, stakeholders should accept that these processes, necessarily established at low scales, are often much less efficient at operational and bigger production scales. Finally, to ensure food security, research programmes on health and bioactivity as well as biofunctionality are proposed.

Conclusions

PEGASUS provides both a current state of the economic potential of the seaweed aquaculture sector and scientific knowledge on the biology of seaweeds, pests and diseases. It also proposes recommendations based on the identification of challenges and bottlenecks that currently prevent the development of the seaweed aquaculture sector in Europe. This should ease the exploitation of the development potential and support the corresponding economy while preserving the marine environment.

PEGASUS should be considered as technical and scientific advice to all stakeholders. First, the methodology applied to PEGASUS is not familiar to scientists, but it is their responsibility to transfer their knowledge to decision-makers, civil society and industry. The Anthropocene era in which we find ourselves provides a new framework for polycentric governance well illustrated by COP21 in Paris (Voß and Schroth 2018). Many actors must exchange and communicate so that political decision-makers can make the best decision for our Earth stewardship (Barbier et al. 2018). When transposed to the seaweed cultivation sector, this should result in all stakeholders involved in the sector, such as seaweed farmers and suppliers, consumers, researchers and policymakers, establishing a collaborative network along the whole value chain in order to guide European strategic development plans. This should also call on economic and political actors to adopt the precautionary approach as the civil society will be made aware of the risks for the marine environment, especially when the high sea system is targeted.

In summary, these recommendations (Table 3) should encourage large-scale reflection on this theme among producers, policymakers, national authorities and scientists when aiming at sustaining the development of this sector

in Europe. In the short term, funding of research programmes should be emphasized, together with a harmonization across the Member States of the European Union regarding seaweed cultivation. The road is long though and progress speed will depend on the amenability of European citizens to diversify their food customs.

Finally, even if PEGASUS focuses on European production, the recommendations provided in the guidelines could be applied worldwide and be approved by all countries (with the corresponding legislation).

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