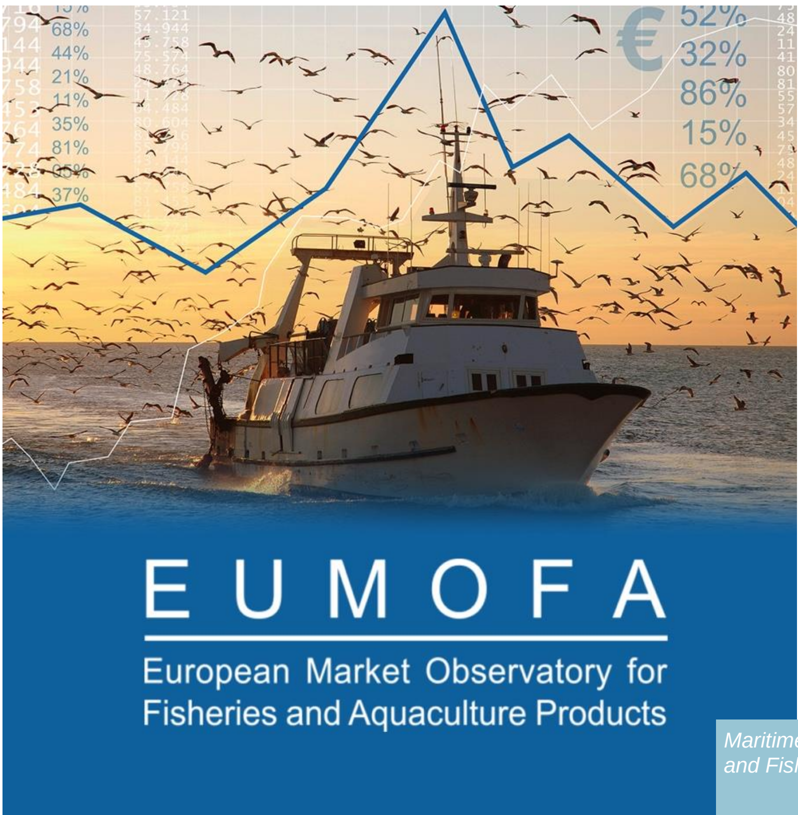
European Commission

BLUE BIOECONOMY REPORT



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LIST OF ACRONYMS

ABO	Algae Biomass Organisation
AEC	Aquatic Eddy Covariance
AI	Artificial Intelligence
AIS	Automatic Identification System
ARPA-E	Advanced Research Projects Agency–Energy
BASF	Badische Anilin und Soda Fabrik
BBE	Blue BioEconomy
BCE	Blue Carbon Ecosystems
BBSRC	Biotechnology and Biological Sciences Research Council (UK)
BECCS	Bioenergy with Carbon Capture and Storage
BETO	Bioenergy Technologies Office (US)
BFIP	Biomass Feedstocks Innovation Programme (UK)
CAGR	Compounded Average Growth Rate
CCS	Carbon Capture and Storage
CICY	Centro de Investigación Científica de Yucatán (Mexico)
CO_2	Carbon dioxide
COP	Conference of the Parties
CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats
CTC	Carbon Trading Credit
DAA	Danish Agricultural Agency
DAS	Distributed Antenna System
DCA	Danish Coastal Authorities
DESs	Deep Eutectic Solvents
DIC	Dissolved Inorganic Carbon
DOC	Dissolved Organic Carbon
DOE	Department of Energy (US)
DW	Dry Weight
EABA	European Algal Biomass Association
EEA	European Economic Area or European Environmental Agency (depending on context)
EIA	Environmental Impact Assessment
EMFAF	European Maritime Fisheries and Aquaculture Fund
EMODnet	European Marine Observation and Data Network
ETIP	European Technology & Innovation Platform
EUMOFA	European Market Observatory for Fisheries and Aquaculture products
FAO	Food and Agriculture Organisation
FATHOMS	Fully Automated, Transportable, Holistic Offshore Macroalgae System
FDA	Food and Drug Administration (US)
GASB	Great Atlantic Sargasso Belt
GC-MS	Gas Chromatography–Mass Spectrometry
GEBCO	General Bathymetric Chart of the Oceans
GFCM	General Fisheries Commission for the Mediterranean
GHG	GreenHouse Gas
GPS	Global Positioning System
ICZM	Integrated Coastal Zone Management
IMTA	Integrated Multi-Trophic Aquaculture
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
ISBR	Integrated Sequential BioRefinery
ITCZ	Intertropical Convergence Zone
LCA	Life Cycle Assessment
LDPE	Low-Density PolyEthylene
LULUCF	Land Use, Land-Use Change and Forestry
MAE	Microwave-Assisted Extraction
MODIS	Moderate Resolution Imaging Spectroradiometer

MS	(EU) Member State
MSP	Maritime Spatial Planning
NFR	Novel Foods Regulation (EU)
NGO	Non-Governmental Organisation
NOAA	National Oceanic and Atmospheric Administration (US)
NPP	Net Primary Production
NTC	Nutrient Trading Credits
OCTs	Overseas Countries and Territories (EU)
PBR	PhotoBioReactor
PCR	Polymerase Chain Reaction
POC	Particulate Organic Carbon
QTL	Quantitative Trait Loci
RAS	Recirculating Aquaculture System
ROV	Remote Operating Vehicle
SFE	Supercritical Fluid Extraction
SLO	Social Licence to Operate
SMEs	Small and Medium Enterprises
SOC	Sedimentary Organic Carbon
UKBCEP	UK Blue Carbon Evidence Partnership
UNFCC	United Nations Framework Convention on Climate Change
UNGC	United Nations Global Compact
WFD	Water Framework Directive (EU)
WG	Working Group
WWF	World Wildlife Fund

GLOSSARY

Aquaculture 4.0 (Sustainable European aquaculture 4.0: nutrition and breeding)[1]: the term embodies the application of Industry 4.0 technologies to aspects of the aquaculture sector, such as the development of sustainable smart breeding programs and feeding methods.

Carbon Capture and Storage (CCS): is the capture of carbon dioxide (CO_2) emissions from industrial processes (e.g., steel and cement production), or from the burning of fossil fuels in power generation. This carbon is then transported from where it was produced, via ship or in a pipeline, and stored deep underground in geological formations. One of the most sustainable approaches to capture and store CO_2 from the atmosphere is photosynthesis, and photosynthetic microorganisms such as microalgae have exhibited promising carbon fixing capabilities[2].

CRISPR: Clustered Regularly Interspaced Short Palindromic Repeats are segments of DNA containing short repetitions of base sequences, involved in the defence mechanisms of prokaryotic organisms to viruses. In this report, the acronym is mostly used to describe a gene-editing technique, in which CRISPR and the RNA segments and enzymes it produces are used to identify and modify specific DNA sequences in the genome of other organisms.

Flocculants: chemicals that promote flocculation (= a process wherein colloids come out of suspension in the form of floc) by causing colloids and other suspended particles in liquids to aggregate, forming a floc. Flocculants are used in water treatment processes to improve the sedimentation or filterability of small particles.

Hydrocolloids: hydrocolloids are gums that are added to foodstuffs in order to control their functional properties, such as thickening or gelling.

Integrated multi-trophic aquaculture (IMTA): The practice which combines, in the appropriate proportions, the cultivation of fed aquaculture species (e.g. finfish/shrimp) with organic extractive aquaculture species (e.g. shellfish/herbivorous fish) and inorganic extractive aquaculture species (e.g., seaweed) to create balanced systems for environmental sustainability (biomitigation), economic stability (product diversification and risk reduction) and social acceptability (better management practices)

Photobioreactor: a bioreactor which incorporates some type of light source. These organisms use photosynthesis to generate biomass from light and carbon dioxide and include plants, mosses, macroalgae, microalgae, cyanobacteria and purple bacteria.

Recirculating aquaculture systems (RASs): These necessitate treatment of outflow water so it can be used as input water. The treatments can be physical and chemical, including sedimentation, ozonification, pH correction and filtration, or they can be biological, using molluscs, seaweeds, plants, settlement ponds, microbiome; or a combination for depuration.

Social Licence to Operate: the term refers to the ongoing acceptance of a company or industry's standard business practices and operating procedures by its employees, stakeholders, and the general public.

Thallus: the undifferentiated vegetative tissue.

[1] https://cordis.europa.eu/programme/id/H2020_DT-BG-04-2018-2019

[2] See P. Jajesniak, H. Ali, T.S. Wong, Carbon dioxide capture and utilization using biological systems: opportunities and challenges, in J Bioprocess Biotech, 4 (2) (2014), doi 10.4172/2155-9821.1000155. See also C.B. Field et al., Primary production of the biosphere: integrating terrestrial and oceanic components, science, 281 (1998), pp. 237-240, doi: 10.1126/science.281.5374.237

FOREWORD

In 2018, EUMOFA released a ground-breaking “Blue bioeconomy: situation report and perspectives” report that provided a comprehensive overview of the blue bioeconomy sector in the European Union. By definition, “blue bioeconomy” incorporates any economic activity associated with the use of renewable aquatic biological resources to make products. Examples of these wide-ranging products include novel foods and food additives, animal feeds, nutraceuticals, pharmaceuticals, cosmetics, materials (e.g., clothes and construction materials) and energy. Businesses that grow the raw materials for these products, or that extract, refine, process and transform the biological compounds, as well as those developing the required technologies and equipment all participate in the blue bioeconomy.

The report was meant to be a one-of-kind publication for EUMOFA, which traditionally deals with typical aquaculture and fisheries, where the fish or shellfish are caught or produced for human consumption. To avoid overlap in analysis of other maritime economic sectors, the Study considers that typical aquaculture and fisheries, where the fish or shellfish are caught or produced for human consumption, is excluded from the analysis. These sectors are already subject to several analysis and reports as standalone sectors, and are already monitored by EUMOFA as part of its ordinary activities.

EUMOFA’s foray into new territory was received quite well by the sector, when the report was presented at the kick-off event of the Blue Bioeconomy Forum in December 2018. In the wake of this success, it was decided to make the Blue Bioeconomy Report a regular publication, to be released every other year.

The 2020 edition covered new topics, such as Integrated Multi-Trophic Aquaculture, innovative uses for fish rest raw material, cell-plant technology and cellular mariculture.

In line with the tradition of addressing cutting-edge topics in blue bioeconomy, this 2022 edition deals with (1) an overview of latest developments of micro- and macroalgae cultivation systems, (2) a focus on sargassum, (3) an analysis of seaweed as blue carbon, and (4) a dissertation on how seaweed can transform regional economies. Each topic is addressed in a separate chapter of the study.

The **first chapter** explores the latest developments of micro- and macroalgae cultivation systems. Seaweed farming and harvesting are still very small-scale in Europe – despite 36% of entries in a global seaweed industry database being in Europe, many are start-ups not yet commercially operational. All three avenues of seaweed use are promising – off-shore and on-land farming for bioremediation and Integrated Multitrophic Aquaculture; ocean-farming for biomass for energy and biorefining; ocean farming and harvesting for carbon capture. The regulatory landscape to obtain licences and permits for seaweed cultivation is often cumbersome, contains too many regulatory actors at national and local level and poses high costs for small companies seeking to farm at sea.

Three other generic issues affect algal development: definition of wastes hampers true sustainable and effective circularity of inputs; demonstration set-ups are still needed at near- or at commercial scale for validation of LCA, economics and investment-worthiness; value-chain pull-through is still needed to firmly position algae as the sustainable alternative to other sources.

Individual elements of microalgal biorefinery processing are being improved – light management, circularity of inputs, energy demands for dewatering, solvents/techniques for bioactives extraction etc – in the interests of economy, sustainability, efficiency and reduced environmental impact.

Wet biomass management technologies will take over from dewatering as route of choice for making use of seaweeds and microalgae. “Aquaculture 4.0” – the use of Information Technology, automated high-sensitivity monitoring, Internet of Things, in-cloud analysis, real-time automated and robotic responses – will become standard for managing large-scale microalgal and seaweed facilities

The **second chapter** focuses on sargassum, a genus of large brown seaweed that spends its life on the ocean’s surface and floats in large masses. Pelagic sargassum plays a crucial role in marine ecosystems, serving as hotspots for biodiversity and productivity in otherwise substrate poor, low-nutrient open-ocean waters. However, the overgrowth of floating biomass and inundation along the coasts have caused negative environmental and socio-economic effects.

The surge in Sargassum blooms across the Atlantic region has led to the proliferation of projects that seek to mitigate its effects. Yet the use of Sargassum around the world is limited to certain niche areas, and there is no real market for the time being. In the Caribbean especially, the use of seaweeds has traditionally been quite limited. As explained in the chapter, albeit holding great potential, most solutions seeking to valorise Sargassum are not commercially mature yet.

The **third chapter** addresses the topic of “seaweed as blue carbon”. Seaweed ecosystems play a crucial role in the marine carbon cycle. There is scientific consensus that seaweed acts as a net sequestrator of CO_2 worldwide, potentially matching levels of sequestration from tidal marshes, mangroves and seagrass ecosystems combined.

If seaweed performance in terms of carbon intake, also called net primary production, is surpassing other marine and terrestrial ecosystems, the complex natural processes leading to a sequestration of the carbon stored in seaweed make it difficult to quantify. There are significant differences in terms of seaweed’s carbon intake, depending on species, type of ecosystem and environmental parameters. So far, science has been unable to give a precise estimation of a given ecosystem – or seaweed farm – carbon sequestration; current methods are not robust enough for blue carbon credits to be extended to seaweed ecosystems and seaweed farming.

Researchers believe that Europe has vast areas suitable for seaweed and macroalgae cultivation[3;4] , but it only accounts for less than **0,25%** of global human-led seaweed production (farming + harvesting). Possible actions to integrate seaweed in climate policies include conservation, restoration and farming, with potential positive effects on both climate and the environment. For the EU to take the best of seaweed’s climate mitigation potential, knowledge gaps have to be addressed, including assessing existing wild seaweed ecosystems in Europe, building a better knowledge of nutrient availability and eutrophication in EU coasts and basins, and evaluating the carbon footprint of seaweed-based products.

Finally, the **fourth chapter** provides an analysis of how seaweed can transform regional economies. The European seaweed industry is both small in scale and regionally imbalanced. There is a growing demand for seaweed products that producers cannot fulfill due to a variety of factors, such as knowledge silos, lack of data transparency, unpredictable production cycles, inefficient supply chains, complex regulatory frameworks, etc. All of these factors disincentivise risk-averse investors and businesses.

The challenges facing the European seaweed industry are not technology-driven. In fact, they seem to be more related to governance and market issues. The reversal of this trend will depend on the stable access to raw material, the development of value-added products and the transfer of expertise between regions where production is well developed and those wishing to develop the industry.

The study team acknowledges with grateful thanks the input, feedback and expertise provided by the wide range of representatives from the bioeconomy sector, who kindly cooperated in the compilation of this study.

[3] Global Potential of Offshore and Shallow Waters Macroalgal Biorefineries to Provide for Food, chemicals and Energy: Feasibility and Sustainability. Lehahn, Y., Nivrutti, I., Golberg, A., 2016

[4] Spatial Analysis of Marine Protected Area Networks in Europe’s Seas II. Agnesi, S., Annunziatellis, A., Chaniotis, P., Mo, G., Korpinen, S., Snoj, L., Tunesi, L., Reker, J., 2020

1 OVERVIEW OF LATEST DEVELOPMENTS OF MICRO- AND MACROALGAE CULTIVATION SYSTEMS

*Chapter authored by Meredith Lloyd-Evans

1.1 Introduction

> To ensure food and nutrition security by 2030, European aquaculture has to sustainably expand in terms of space, production and new value chains, exploring and enhancing innovation opportunities offered by sustainable and resilient aquaculture production systems, implementing the circular economy principles and increasing social acceptance of the corresponding activities and products.
> *Source: Atlantic Strategy Call Blue Growth – Sustainable European aquaculture 4.0*[1]

The EU's Food from the Ocean Report[2] of 2017 and the accompanying scientific evidence report[3] were influential in confirming the growing attention on lower trophic levels, specifically invertebrates and seaweeds, as the way forward. The EU's Farm to Fork strategy[4] specifically mentions 'well-targeted support for the algae industry, as algae should become an important source of alternative protein for a sustainable food system and global food security'. The EC communication on sustainable, competitive aquaculture[5] recognises that "the farming of algae …, when appropriately managed, can offer many ecosystem services, [including] the absorption of excess nutrients and organic matter from the environment or the conservation and restoration of ecosystems and biodiversity". The Blue Economy Report 2022[6] also confirms that "[the] most notable sub-sector in blue bioeconomy is the algae sector. Available socio-economic [data] estimate that algae production in Europe generates an annual turnover well above €10 million in the MSs (Member States) with the largest number of production facilities (France, Spain and Portugal)." And the 2022 EU Algae Initiative's underpinning rationale is that "[the] farming of algae can contribute to achieving the EU's objectives in terms of decarbonisation, zero pollution, circularity, the preservation and restoration of biodiversity, the protection of ecosystems and the development of environmental services. Algae can replace fossil-based products, and serve as raw material for plant biostimulants, bio-based chemicals and other materials, and biofuels."[7]

The EU Algae Initiative (*Towards a Strong and Sustainable EU Algae Sector*) is the most important document to have been produced to-date in the efforts for algal advancement. It aims to "support the production, safe consumption and innovative use of algae, address the challenges and opportunities of algae farming and propose concrete actions". It sets out and summarises these relevant challenges, strategic goals and actions, represented in the image below. Rather than repeating these in detail, this chapter will often refer to the two European Commission documents that comprise this blueprint for actions to 2030 and a little beyond[8], a period when Seaweed for Europe is suggesting that more than

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[1] https://atlantic-maritime-strategy.ec.europa.eu/es/funding/calls/call-blue-growth-topic-sustainable-european-aquaculture-40-nutrition-and-breeding

[2] *Food from the Oceans - How can more food and biomass be obtained from the oceans in a way that does not deprive future generations of their benefits?* High Level Group of Scientific Advisors Scientific Opinion No. 3/2017 European Commission 2017

[3] https://sapea.info/topic/food-from-the-oceans/

[4] https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en

[5] EC communication on sustainable, competitive aquaculture 2021-2030 COM(2021) 236 final 12.5.2021

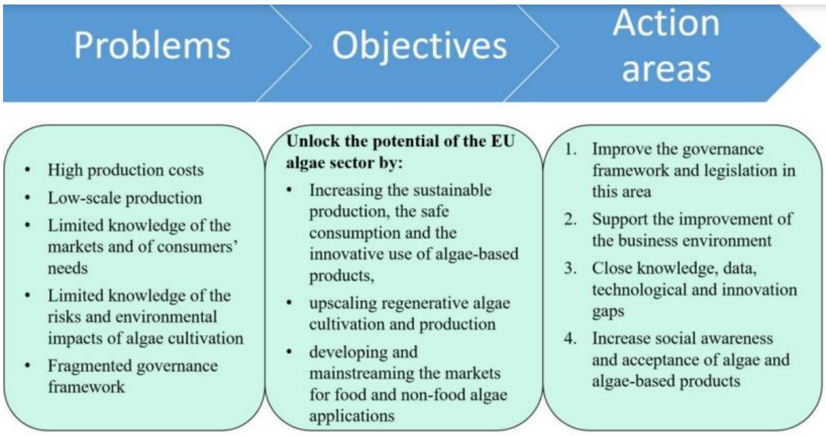
[6] EU blue economy report 2022-KLAR22001ENN.pdf

[7] Commission Communication *Towards a Strong and Sustainable EU Algae Sector* COM(2022) 592 final https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2022:592:FIN

[8] COM(2022) 592 & the Commission Staff Working Document *Blue Bioeconomy – Towards A Strong And Sustainable EU Algae Sector* SWD(2022) 361 final, accompanying COM(2022) 592 https://oceans-and-fisheries.ec.europa.eu/system/files/2022-11/swd-2022-361_en.pdf

8 million tonnes of seaweed need to be produced each year[9]. The Algae Initiative documents also summarise much of the context, including policy and legislation. Algal advancement as prefigured in the EU Algae Initiative will closely link industry with circularity and environmental sustainability.

Figure 1.1: Unlocking the potential of the EU algae sector



Source: EU Algae Initiative COM(2022) 592 final

The major drivers for further development of aquatic algae include:

- Capturing residual materials as valuable contributors to Circularity;
- Mitigating Climate Change and contributing to Carbon capture (or sequestration, re-use efficiency);
- Reducing land use and abuse;
- Finding alternatives to animal- and fish-derived proteins and oils for human food, petfood and animal feed;
- Finding alternatives to land-based biomass for food, feed and fuels;
- Finding alternatives to petrochemicals for a wide range of industrial and consumer applications;
- Pre-empting and reducing plastic wastes from packaging, textiles and other products;
- Re-wilding the natural environment and re-balancing the seas via regenerative ocean farming.

Globally, there is a clear impetus to increase the production of algae. Marine algae contribute to at least 50% of the oxygen on Earth and absorb carbon dioxide in return, in a way that suggests they have a contribution to make in counteracting anthropogenic CO_2 emissions. Estimates of the relative contributions of microalgae and seaweeds to global oxygen are not available, but *Prochlorococcus* phytoplankton is estimated to contribute to 20% of the oxygen[10], and research suggests that the total output of Chinese farmed seaweed might contribute to 2.5 million tonnes of oxygen annually, with an increase of 21% daily dissolved oxygen in the top 3 m of the water column[11]. Extrapolating FAO (Food and Agriculture Organisation) data suggests the recorded world output of farmed seaweeds and aquatic plants might generate c. 4.3 million tonnes oxygen yearly; clearly, wild seaweeds would produce orders of magnitude more.

[9] https://www.seaweedeurope.com/wp-content/uploads/2020/10/Seaweed_for_Europe-Hidden_Champion_of_the_ocean-Report.pdf

[10] https://oceanservice.noaa.gov/facts/ocean-oxygen.html

[11] Gao G, Gao L *et al.* (2022) The potential of seaweed cultivation to achieve carbon neutrality and mitigate deoxygenation and eutrophication *Environ Res Lett* 17: 014018 doi: 10.1088/1748-9326/ac3fd9

Algae as a term is rather broad and includes seaweeds (macroalgae) and phototrophic marine and aquatic microalgae that possess light-trapping molecules such as chlorophyll and phycobilins; cyanobacteria ("blue-green algae") that are bacteria with chlorophyll for photosynthesis; heterotrophic microalgae that have lost chlorophyll and are reliant on external nutrients; and mixotrophic aquatic microorganisms that use both light and external nutrients for growth. Industrial microalgae are grown on-land. Farming of phototrophic organisms is limited by the efficiency of light access to the biomass. Controlled production of heterotrophic or mixotrophic microalgae, liberated from complete reliance on light, is often more efficient and productive than photoautotrophic culture and allows a move from open-pond cultivation to enclosed systems, such as photobioreactors or vessels based on fermentation systems. Advanced technologies are possible in these circumstances.

The EU has 66,000 km of coastline, 185,000 km if Iceland, Norway and Turkey are included, 5 million km^2 of marine area, 715,000 km^2 of territorial waters and 560,000 km^2 of coastal zones in 24 EEA (European Economic Area) countries[12]. Much of the coastline is subject to MSP (Maritime Spatial Planning) and TSP (Terrestrial Spatial Planning) considerations, involving commercial and small-scale fishing, aquaculture, recreational sailing and shipping routes, use by various industries for outputs e.g. dredging for building materials or inputs e.g. sewage, wastewater and surface-water outflows, and land-use for industry, services, housing and ports. These will make it difficult to increase the area of on-shore farming and on-shore processing facilities for seaweed and near-coast activities for either type of algae.

Macroalgal production is almost entirely a maritime activity, with some on-land farming and with seed production easiest to do in land-based laboratories. Though seaweed farming can be linked with other aquaculture when the components can use the same infrastructure, typically with seaweed and mussels grown on lines, harvest times are often different, adding to cost and complexity, and farms are plagued with overgrowth by unwanted algae and invertebrates.

Seaweed farming concepts are increasingly moving in two diverging directions:

- into deeper water, potentially using infrastructure of other off-shore activities such as wind-farms ("Wind+Weed") - see North Sea Farmers' plan for a 160-hectare commercial-scale Ocean Farm[13] - or as extensive, floating, tethered/anchored or even mobile arrangements covering tens or, conceptually, thousands of hectares and avoiding much of the MSP difficulties of closer-to-shore installations; in these conditions, brown seaweeds, mainly the kelps, are favoured;
- onto land, in raceways or tanks, equivalent to and integrated with trout and salmon RASs (Recirculating Aquaculture Systems), or in juxtaposition with horticulture, or in tidal saltwater earthen ponds as practiced by AlgaPlus Portugal, where growing conditions and the impacts of diseases can be better controlled; in these conditions, green and red seaweeds are favoured;
- for the seed-production and seeding stages of seaweed cultivation, on-land units are used;
- wild harvesting of seaweeds is a feature of current production of biomass for food, feed and fertilisers; both farming and collection of wild floating seaweed are proposed on a huge scale for ocean carbon-sinking; for these uses, green seaweeds such as Ulva and brown seaweeds such as Sargassum and kelps are favoured.

Why are algae so attractive and potentially on the verge of major expansion as essential elements of the Green Deal and the Circular Economy is because of the enormous diversity of applications from their use?

[12] See https://www.eea.europa.eu/themes/water/europes-seas-and-coasts
[13] https://www.northseafarmers.org/projects/north-sea-farm-1

Partly because they lack the lignin content of terrestrial feedstocks, algae are particularly suitable as feedstocks for the biorefining industry in the production of conventional biofuels, such as ethanol and butanol, and advanced fuel boosters, such as furan-based molecules. Fine chemicals such as levulinic acid and fibres from seaweed can be used in the production of renewable chemicals including furanics, lactic and succinic acids to replace petroleum-based chemicals and polymers. The content of macro- and micro-nutrients, plant-growth regulators, phytohormones, and saccharides improve soil quality, stimulate root and plant growth, and activate defence mechanisms which enhance plant productivity. Seaweed in the diet of ruminant livestock significantly reduces production of methane. Seaweed bioactives are used in the prevention of diabetes, hypertension, cardiovascular diseases, obesity and mental degeneration disorders and in cosmetic applications like anti-aging.
Adapted from TNO 2018[14]

The ***Safe Seaweed Coalition***, a network which is increasingly important as a driver of policy and action, encapsulates the reasons why they support seaweed development in their vision of a Seaweed Revolution:

Seaweed can add 10% to the world's present supply of food using just 0.03% of the oceans' surface;
Seaweed and microalgae are responsible for 50% of photosynthesis on Earth;
By 2050, seaweed production could absorb 135 million tons of CO_2 a year and 30% of all nitrogen entering the oceans from land-based pollution.
Source: Safe Seaweed Coalition, accessed 2022[15]

Together, these attributes for microalgae and seaweeds are encouraging at the top level an acceptance of algae as part of the solution, not part of a problem, and at the practical level, innovation in biomass production and harvesting in the seas and on land, and processing for major commodity uses as well as splitting out specific components through biorefinery systems.

In addition to relieving land-pressure, part of the attraction of using algae in the Circular Economy concept is that the efficiency of solar-to-chemical energy conversion via algal photosynthesis is 4%-10%, compared with 0.5%–2.2% in crops[16], something that can be captured very easily in today's photobioreactors (PBRs) for microalgae and in seaweed farming in the sea and on land.

For microalgae, land-based cultivation is a given. The challenge is in reducing the costs of inputs including energy, heat and nutrients, as well as balancing scale-up sizes with environmental footprints. Integration with industries or systems producing nutrients as outflows is capable of making enormous contributions to circularity and carbon capture/re-use. An attractive input in such a system might be the 'waste' liquid outflows or the anaerobic digestates from animal farming, households, agriculture, food-processing, sewage treatment or lignocellulosic processes[17]. These contain elemental ions, phosphorus and nitrogen (mainly ammonia), bicarbonates and high-stability carbon, often with CO_2 or biogas as another nutrient input.

The further challenges for their use as inputs to microalgal production depend on the target outputs. For animal feed or plant biostimulants the question is how to extract the nutrients, including essential elements (zinc, iron, manganese, nickel, molybdenum, copper, calcium, potassium) and convert to microalgal biomass without concentrating the undesirable components that might affect production or

[14] For example, in Stimulating a biobased economy by optimising the seaweed processing train ECN TNO 2018, promoting the Seaweed Processing Facility, but equally applicable to microalgal fractionation and prospects

[15] https://www.safeseaweedcoalition.org/the-seaweed-revolution/

[16] Dębowski M, Zieliński M *et al*. (2020) Microalgae Cultivation Technologies as an Opportunity for Bioenergetic System Development—Advantages and Limitations *Sustainability* 12: 9980 doi: 10.3390/su12239980

[17] Tawfik A, Eraky M et al. (2022) Cultivation of microalgae on liquid anaerobic digestate for depollution, biofuels and cosmetics: a review Env Chem Letters doi: 10.1007/s10311-022-01481-2

the consumer. For bioenergy the main challenge is how to achieve economic conversion without energy-intensive de-watering and drying. For high-value targets, it is how to preserve the components during transportation and processing, and how to get high yields without using environmentally-suspect tools such as toxic solvents.

The EU Algae Initiative has four Action Areas. It captures the need to close gaps in knowledge, data, technologies and innovation in its Action Area 3[18]. The others concern Governance and legislation, Business Environment and Social awareness and acceptance and are also highly relevant. Definite actions that the Commission will take include:

- Integrating algae sector knowledge into the EU Aquaculture Assistance Mechanism.
- Investigating the feasibility of creating a centralised data-source for all algae-related econometric data.
- Supporting, via existing funding programmes, new projects for microalgae that move beyond lab-scale photobioreactor and biorefinery work, incorporating newer technologies such as precision fermentation, cellular mariculture and cell-free systems, or link production with aquaponic crop production; and for seaweeds, development of improved scalable systems including IMTA, off-shore, multi-use and on-land.
- Preparing the ground for a centralised seaweed biobank with a network of regional biobanks to support seaweed cultivation and research and maintain biodiversity.
- Promoting open-access pilot sites in conjunction with accelerator-scheme innovation vouchers.
- Funding production of an ‘algal toolkit’ for new entrants, as a practical guide to setting up and dealing with the chosen value-chains, including regulatory and licensing aspects.
- Clarifying the regulatory questions related to the waste status of inputs for algal culture.
- Preparing specific guidance on replacing fishmeal in fish feeds with algae-based feeds.
- Commissioning a number of fact-finding studies including:
    - identifying the appropriate and feasible opportunities to use seaweeds in the EU as carbon sinks and in climate change mitigation;
    - quantifying uptake of nutrients that otherwise contribute to eutrophication or to unused waste outflows;
    - compiling existing best practice and procedures for licensing and permits across the EU;
    - establishing the exact scale and nature of wild seaweed harvesting and beached seaweed collection in the EU and monitoring schemes in place.

This provides the most comprehensive policy approach to algal advancement that the EU has adopted to-date. The major action taken to-date is establishment of the platform EU4Algae[19]. The importance of networks and platforms is increasing, as exchangers of best practice and scientific knowledge, producers of fact-based lobbying material for sensible and realistic economic and regulatory support systems, and recruiters of investment. The single most important factor mentioned in the context of market success by commentators is that there is a need to accept the diversity of applications and to secure the markets in parallel with production – in other words, end-user, consumer and investor’s commitment rather than just technology development. EU4Algae is expected to drive the policy of the future that will be reflected in EU actions and national innovation support programmes and in

[18] See pp 42-48 of SWD(2022) 361 final

[19] https://webgate.ec.europa.eu/maritimeforum/en/frontpage/1727

simplification, integration and harmonisation of regulatory, licence and permit systems, which at the moment are regarded as one of the biggest barriers to growth.

This chapter does not touch on Human Resources, training and education, though these are a vital part of embedding technological advances into productive businesses. Nor does it examine the geographic and maritime variations across Europe that will definitely have an impact on feasibility of advancement and deployment of different technologies, embedded in algal systems. Technological advancement is occurring on many different fronts and in many parts of the algal value-chains from production to products. One of the early tasks of the EU Algae Initiative is to support creation of a database of algae-related projects in the EU, which is being progressed via EU4Algae. The initial database is expected to include c. 750 projects; this chapter will be mentioning only a fraction of the projects, programmes, research and achievements.

1.2 Challenges and barriers

Challenges and barriers are well-described in the EU Algae Initiative, as summarised in Figure 1.1 above[20]. There are six identified, applying equally to microalgae and seaweeds, each of which can give rise to a programme of coherent and effective actions:

- Low production volumes;
- High production costs;
- Limited knowledge of market and consumers;
- Limited knowledge on risks and impacts of an expanded algae production;
- Fragmented governance framework.

The current status of seaweeds in Europe has been summarised as an internal market failure, in that "because it is so easy and cheap for algae companies to import algae, European production is slow-moving with only a few species and there are no large farms, which impedes a proper economic analysis. Regulation lags behind actual positive developments, aquaculture is behind agriculture and there are confusing waste policies and labelling requirements for beach-wrack harvests, for which there is little data on environmental impacts"[21]. At the most fundamental level of algal farming, there is still insufficient knowledge about disease management, interactions between species or between the desired biomass and cultivation variables, and funding is needed for acceleration of biomass volumes, early warning of new pests and development of high-throughput monitoring and tracking tools.

The interview-based survey carried out as part of the Interreg project EnhanceMicroalgae reveals some of the concerns of those working in the algal sectors[22].

issue	comments
REGULATIONS	These are the most critical obstacles to the industrial development of microalgae; legislation on microalgae is complex and needs significant simplification. It suffers from a critical lack of specialised personnel and requires special attention in the training of policymakers. With respect to algae and algal products for human food, the Novel Foods Regulation is too restrictive and the complete list of microalgae-related products authorised in Europe is very limited. There is a lack of uniformity in the enactment of legislation between EU countries, including planning and building

[20] Presented in more detail on pp 15-19 of SWD(2022) 361 final, with the context and rationale for action on pp 19-23

[21] GRASS Macroalgae conference 6-7 May 2021 SUBMARINER Blue Platform

[22] Rumin J, Gonçalves de Oliveira Junior R *et al.* (2021) Improving Microalgae Research and Marketing in the European Atlantic Area: Analysis of Major Gaps and Barriers Limiting Sector Development *Mar Drugs* 19: 319 doi: 10.3390/md19060319

issue	comments
	regulations and start-up incentives. With respect to exports of European algal produce, certain species and related products are allowed in Europe but are banned elsewhere eg by China.
GENETIC TOOLS	Complete and accurately-annotated genomes remain few in number, though there is a large amount of data, correlations with phenotype and performance are still lacking and latest techniques [such as CRISPr-Cas9] have only recently been used. Scientists are very likely to work with incorrect data, leading to a series of errors. The small number of species that are cultivated, compared to the immense biodiversity of species and strains, hinders development. The absence of correlates between genes and performance characteristics makes strain selection for cultivation more difficult.
MICROBIAL CONTAMINANTS IN LARGE-SCALE CULTURE	The bacterial, viral and fungal diseases and grazing predators are not well studied and identified, and a scientific effort must be made to improve knowledge and data in omics concerning their interactions with microalgae. This technological barrier would take longer to overcome, according to more than half of the respondents.
TIMESCALES FOR DECISIONS IN RTI FUNDING	The market changes very quickly while waiting for European research funding, and reducing decision-times needs discussing for future programmes, compared with the speed and flexibility of national support.

The algal industries, apart from marine hydrocolloids, are caught in multiple binds: import substitution by EU product requires much greater production at competitive price, but the development of both seaweed and microalgal biomass production is still too small-scale and costly overall to justify investment in further scale-up; targeting niche markets with higher-value products than feed, fertiliser and fuel can be satisfied by smaller-scale production and higher-cost processing but this inhibits the step-changes needed for technological advancement; the legislative framework in Europe appears to handicap indigenous production and products whilst not policing imported products adequately for either their approval status or their content of undesirable contaminants such as cadmium; a lack of rapid-response capability from authorities means that producers cannot take advantage of market opportunities such as the failure of Asian nori production. These challenges will be tackled as part of the Algae Initiative.

The ***UNGC (United Nations Global Compact) Platform for Sustainable Ocean Business*** in its Practical Guidance[23] stresses that outside Japan, China and South-east Asia, seaweed production and utilisation is still an emerging industry at the start of a growth phase. It identifies policy and knowledge gaps:

Policy gaps	• Lack of spatial planning and operationalisation of existing spatial plans • Lack of uniformly accepted monitoring, data-sharing protocols and third-party certification to validate the safety and sustainability of seaweed production • Lack of biosecurity policies and sustainability protocols pose a major concern and risk to both farm productivity and wider ocean health • Lack of legal framework regarding licensing procedures specific to seaweed (including guidelines concerning alien species and carrying capacity) • Marine planning and aquaculture policy often do not include seaweed aquaculture
Knowledge gaps	• Lack of experience on the impact of seaweed cultivation on local ecosystems outside of Asia • Establishment and maintenance of seaweed farming systems • Lack of knowledge on best management and cultivation/harvesting practices from seaweed farmers/harvesters towards end-users • Limited knowledge or understanding around the livelihoods of small-scale seaweed farmers in the Global South

[23] *Practical Guidance for the UN Global Compact: Sustainable Ocean Principles SEAWEED* published 1.1.2020

	• Lack of commercial knowledge of seaweeds potential role in bioremediation and IMTA including co-location offshore with renewable energy platforms • Lack of end consumer knowledge on seaweed – in western markets – its application, benefits and potential contribution to climate change to boost demand • Lack of investment in seedbanks and hatchery programs; disease and climate-resistance strains of seaweed are unavailable in many countries • Technology and scalability barriers, such as cost effective and robust positioning, harvesting, remote sensor and processing solutions • Lack of appropriate "ocean monitoring solutions" and IT systems to maximise farm productivity • Lack of investment in the application and marketing side of seaweed production
Environmental challenges	• Lack of nutrients for seaweed cultivation in some deep-sea offshore areas due to limited upwelling compared to coastal waters • Run-offs from adjacent land-based agriculture, incorporating pesticides, heavy metals and insecticides • Climate change effects, such as warmer water temperatures and ocean acidification, may reduce seaweeds' resilience to disease outbreaks and create harsher farming environments

Adapted from Practical Guidance for the UN Global Compact: Sustainable Ocean Principles SEAWEED

For seaweed in the oceans, the challenges include:

- For farming, developing the technologies needed for efficient and effective working at distance from the shore or in conjunction with other activities such as in 'Wind+Weed'; advent of advanced robotic systems for use in automated harvesting will aid this aspect;
- For wild harvesting it is mainly the limitations imposed by permit authorities and supported by environmental groups, due to concerns about environmental impacts of harvesting methods and recovery times of kelp forests: Europe has the largest global standing biomass of *Laminaria hyperborea*, c. 100 million tonnes (c. 20 million tonnes in Scotland[24] and c. 60 million tonnes in Norway[25]), with a potential sustainable harvest of 1.5 million tonnes each year in Norway alone, but currently perhaps 250,000-300,000 tonnes of kelp are harvested due to licence and permit limitations[26]; advanced monitoring for Environmental Impact Assessments of kelp harvesting may help make more use of the potential;
- For the concept of carbon-sequestration by seaweed, by sinking biomass or making use of it for soil-improving biochar, either by collection or farming, it is the sheer scale of activities needed to make any impact:
    - the current total annual production of seaweeds and aquatic plants (c. 36 million tonnes farmed and wild-harvested according to latest FAO statistics) is only 0.04-0.05% of the 9 billion tonnes of cultivated seaweed that would be needed to capture the 1 billion tonnes of carbon removal required by 2025[27]; realistic estimates are that by 2050, 0.1 per cent of the ocean could be producing seaweed, as a food source, materials and chemicals, 15 times more seaweed than at present[28]; even if one thinks that "every little helps", current technologies for farming or harvesting and processing

[24] https://marine.gov.scot/sites/default/files/r3007_wild_seaweed_harvesting_scoping_report_17july2018lr_0.pdf

[25] Gundersen H, Christie CH *et al.* (2011) *Utredning om CO_2-Opptak i Marine Naturtyper* Norwegian Institute for Water Research (NIVA), Oslo, Norway

[26] https://alginor.no/

[27] Mackie D (2022) Poor Seaweed – such Great Expectations, Seagriculture June 2022 + personal communication

[28] Duarte *et al.* (2017) & Froehlich *et al.* (2019) referenced in *Seaweed Revolution A manifesto for a sustainable future* Lloyd's Register Foundation 4 June 2020

seaweeds would have to advance immeasurably, to satisfy even a fraction of the 6 billion tonnes of carbon removal needed per year to maintain global warming at +1.5°C in 2050, projected by the UN's IPCC in its Sixth Assessment Report[29], as well as produce seaweeds for food, feed, energy and biorefining;

- the Climate Foundation estimates that Marine Permaculture seaweed farming can abstract 50 tonnes of CO_2/hectare/year[30], so even to achieve a respectable 1%-5% offset of the 2025 target would require 20 million-100 million Ha (200,000-1 million km^2) of active ocean-farming or collection areas for carbon sequestration alone;
- there is also a sound scientific argument that seaweeds lock up carbon very effectively themselves, producing dissolved and particulate organic carbon, both of which eventually become immobilised in ordinary sea- and ocean-bed sediments, so that existing kelp forests already sequester large amounts of carbon and simply establishing new kelp forests will make a contribution[31];
- and there is some doubt that even planting seaweed forests would lock-up carbon, due to overall emission effects of all the other organisms in the seaweed biome and environment[32]. This argues that full carbon accounting is needed in EIAs and LCAs.

About 60% of world farmed seaweed, over 20 million tonnes in 2019[33], is generated in China. *Saccharina japonica* and *Undinaria pinnatifida* kelps are regarded as indispensable strategic resources for China, Japan and Korea. China's problems are currently driving developments in approaches to genetics, production and monitoring, reviewed by Hu *et al*. (2021)[34]. The problems include declining germplasm diversity, degradation of agronomic traits, the presence of polluted environments, changing ocean conditions, increasing anthropological interference, genetic cross-contamination between wild and farmed kelp populations, and the impacts of ocean warming and ocean acidification. These are all relevant for Europe. In addition, in aiming for new markets, there will be a need to move beyond the easiest-to-cultivate seaweed species to those that generate the best content of desired products, which may well be a challenge with respect to behaviour in Europe, identifying appropriate indigenous species, or genetically editing them.

For all types of algae, a range of environmentally-focused EU Directives and Regulations have inhibitory effects on selection of new species that might have better characteristics for production, processing and markets, including the Habitats Directive 92/43, the Environmental Impacts Assessment Directive 97/11, Regulation 511/2014 concerning compliance with the Nagoya Protocol of the Convention on Biological Diversity (regarding ownership and compensation for use of bioresources), and Regulations 708/2007 and 1143/2014 concerning alien, locally-absent and potentially-invasive species. On the other hand, this drives exploration and adaptation of local, un- or under-utilised species, such as the work by AlgaPLUS of Portugal, with other Portuguese and Brazilian partners and EABA (the European Algal Biomass Association), to establish *Codium tomentosum*, *Ulva ohnoi* and *U rigida* as new species for food, in earthen ponds and co-cultured with fish in IMTA[35].

[29] https://www.ipcc.ch/report/ar6/wg3/

[30] https://www.climatefoundation.org/questions-and-answers.html

[31] Filbee-Dexter K and Wernberg T (2020) Substantial blue carbon in overlooked Australian kelp forests *Sci Rep* 10: 12341

[32] https://theconversation.com/kelp-wont-help-why-seaweed-may-not-be-a-silver-bullet-for-carbon-storage-after-all-178018]

[33] *FAO Yearbook Fishery and Aquaculture Statistics 2019*, FAO Rome 2021

[34] Hu Z-M, Shan T-F et al. (2021) Kelp aquaculture in China: a retrospective and future prospect Rev Aquac 13: 1324–1351 doi: 10.1111/raq

[35] Case Study 1 of the EU project AquaVitae https://aquavitaeproject.eu/wp-content/uploads/2022/05/AV_CS1_practice_abstract_vfinal.pdf

The complexity and cost of establishing algal operations and commercialising the products will need to simplified over the world: pre-permit full-scale environmental audits and impact analyses, as required in the USA for seaweed farms, may cost more than $1 million before any buying, installation and operating costs; producing the data and submitting this for Novel Foods Regulation approval in Europe may cost more than €200,000 and 2-3 years of sales-foregone.

The complexity of State procedures in EU and USA and separation from central policy mean, for example, that in France, for on-land seaweed production, the algal farming and the seawater supply are dealt with by different ministries who do not communicate with each other; or in Washington State, 9 different agencies are involved in issuing and agreeing a seaweed farm permit[36]. Even in the EU, with respect to trade tariffs algae are plants, while for production they are aquaculture species.

1.3 Policy context

Policy exists at supranational, regional and national levels. Though made by Government, it can be strongly influenced by cross-stakeholder groupings (see below and in the Networks sub-section). At supranational level, the United Nations has had a very high degree of influence, partly due to global acceptance of its sustainability targets, partly by the frequency of COPs (Conferences of the Parties) related to climate, sustainability and, essentially, the feasibility of the future. The UN activities will not be discussed here, but they have driven establishment of bodies like the Safe Seaweed Coalition and form an umbrella for EU activities such as the Algae Initiative, which is the policy output that will now have most impact on algal advancement in Europe.

The EU Algae Initiative aims to increase sustainable production, ensure safe consumption and boost the innovative use of algae and algae-based products in the European Union. An inception impact study and consultation took place in 2021, and the finalised Algae Initiative document was published 15th November 2022[37], along with the Staff Working Document that sets out the background and actions in more detail[38]. Of the actions that were taken before finalisation, the most prominent is establishment of the EU4Algae platform project[39] to network all interested parties in identifying concrete actions in the different sectors of algal activity, value-chain orientated as well as underpinning.

In evolutionary terms, this was pre-figured and supported by the EU's Horizon 2020 Programme "Sustainable European aquaculture 4.0: nutrition and breeding", the European Green Deal, the European Commission's Communication on sustainable and competitive aquaculture 2021-2030 and the Blue Bioeconomy Forum's considerations. The context and relevance of these is explained in Section 1 of COM(2022) 592 and need not be spelled out in more detail here. Suffice it to say that a tremendous potential for algae is fully-recognised, in a way that suggests top-down support of efforts to overcome the existing barriers and challenges. Further, albeit not exclusively targeting macro- and microalgae, the European Commission has set up the BlueInvest initiative, which aims to boost innovation and investment in sustainable technologies for the blue economy, by supporting readiness and access to finance for early-stage businesses, SMEs and scale-ups. As of today, its pipeline includes several algae-related projects[40].

National activities are also favouring the use of seaweeds as habitat restorers, bioremediators and sources of biomass, for example, the UK's new cross-Administration UK Blue Carbon Evidence Partnership (UKBCEP), set up in 2022 to advance the evidence base on blue carbon habitats in UK

[36] https://www.pewtrusts.org/en/research-and-analysis/blogs/stateline/2022/03/07/seaweed-farming-has-vast-potential-but-good-luck-getting-a-permit

[37] Commission Communication *Towards a Strong and Sustainable EU Algae Sector* COM(2022) 592 final

[38] Commission Staff Working Document *Blue Bioeconomy – Towards A Strong And Sustainable EU Algae Sector* SWD(2022) 361 final, accompanying COM(2022) 592

[39] https://webgate.ec.europa.eu/maritimeforum/en/frontpage/1727

[40] https://webgate.ec.europa.eu/maritimeforum/en/pipeline/projects/4361

waters, as part of a commitment to protect and restore blue carbon habitats[41], which has instigated a £140 million Natural Capital and Ecosystem Assessment programme, and the Dutch Government's North Sea 2050 Spatial Agenda, which includes multi-use activities such as seaweed, mussel, fish IMTA, and 'Wind+Weed' and 'Wave+Weed' (seaweed co-location with wind-turbines and wave-energy capture resp.), as well as recognising the bioremediation potential of seaweeds[42].

Policy initiatives established by non-governmental bodies, notably the Lloyd's Register Foundation, with its *Seaweed Revolution*[43], the Safe Seaweed Coalition[44] and the WWF (World Wildlife Fund), with actions Blue Finance and Nature-Positive Business are already having strong impacts on the acceptability of algal endeavours as contributors to food security and quality, environmental action and the fight against global warming, and replacement of petrochemicals. This adds to the attraction of microalgal and seaweed initiatives as investment targets, something that will be needed for full-scale industrial activities.

With respect to carbon emissions and carbon offsets, the EU Algae Initiative recognises the role that algae might have in this, and for greater impact it is likely to be important to get algae, especially seaweeds, higher on the agenda of the IPCC (Intergovernmental Panel on Climate Change) and onto that of the Coalition for Negative Emissions[45], which has stressed the need for "robust, liquid and transparent markets for trading negative emissions credits, and supply-side financing for individual projects". The IPCC has noted low confidence in the impact of increased sinking or farming due to lack of data and that "the climate mitigation effectiveness of other natural carbon removal processes in coastal waters, such as seaweed ecosystems [...] are smaller [than coastal ecosystems such as mangroves or seagrass] or currently have higher associated uncertainties. Seaweed aquaculture warrants further research attention"[46]. The approach to greenhouse gas removal will necessarily be a portfolio one. McKinsey & Company tantalisingly illustrate one of their articles on climate goals with a microalgal PBR array[47], though neither the article nor the report it accompanies mention algae or seaweed. In future, the abbreviation BECCS may become more commonly applied to algal projects – bioenergy with carbon capture and storage.

1.4 Organisations, networks and facilities

These resources are an essential part of moving algal knowledge and development forward. Organisations and networks are dedicated to bringing interested parties together, with various aims, sometimes to bring focus to industrial activities, sometimes to generate critical mass for actions such as funding or lobbying. They are often supported by local or national governments, may sometimes act as channels for government funding of projects and initiatives, and are invaluable for their efforts in spreading knowledge, best practice and access to facilities. They can be national, regional, international or web-based virtual initiatives. At Government level, they represent attempts to develop cross-administration consensus for action within policy frameworks.

At international level, the most active body is currently the Safe Seaweed Coalition[48], which sprang from the United Nations Global Compact[49] and discussions within the Lloyd's Register Foundation. It is

[41] https://mobile.twitter.com/ukbluecarbon

[42] https://www.noordzeeloket.nl/en/policy/noordzee-2050/@166956/north-sea-2050/

[43] *Seaweed Revolution A manifesto for a sustainable future* Lloyd's Register Foundation 4 June 2020

[44] https://www.safeseaweedcoalition.org

[45] https://coalitionfornegativeemissions.org/

[46] IPCC's *Special Report on the Ocean and Cryosphere in a Changing Climate* – see Chapter 5 p 524 https://www.ipcc.ch/srocc/

[47] https://www.mckinsey.com/capabilities/sustainability/our-insights/how-negative-emissions-can-help-organizations-meet-their-climate-goals

[48] https://www.safeseaweedcoalition.org

[49] https://www.devex.com/organizations/united-nations-global-compact-un-global-compact-56395

supporting the Food and Agriculture Organisation's Codex Alimentarius in including seaweeds in its guidelines on food safety; the FAO's Committee on Fisheries and Codex Alimentarius Commission agreed in September-November 2021 to both seaweeds and microalgae being considered. It also has funded two project calls so far, in Spring and Autumn 2022, for proposals on "the topics we should be investigating and the projects we should be launching". The European Commission has input into the Advisory Panel and the WWF's programme on Advancing Aquaculture for Climate Gains is also represented.

Examples of national and local networks, groups and platforms include:

- The USA's **Algae Biomass Organisation** ABO[50], which promotes development of viable commercial markets for renewable and sustainable commodities derived from algae and has lobbied to get algae accepted by Government as agricultural and food crops and subject to the same policy and regulatory approaches, so that seaweed farming and microlgal cultivation is treated in the same way as land-crops with respect to financial opportunities. Membership includes large industrial corporations in sectors into which algal end-products can be supplied as well as innovative and small producers and technology companies, and national and state research establishments;
- **Algae-UK**, a network supporting researchers and others interested in the exploitation of algal products and processes in industrial biotechnology[51], supported by the biotechnology and biological sciences research council BBSRC and acting as fund-holder for projects in algal advancement[52]. Much of their effort is in counteracting lack of knowledge about how and under what conditions algae produce their metabolites;
- the UK's **Blue Carbon Forum**, founded in 2022 to address the general absence from carbon accounting and international policy of the marine biome's ability to sequester and store carbon, creating cross-sector collaboration to "strengthen the link between climate mitigation and ecological benefits; improve communications and build support for nature-based solutions; standardise and align methodologies to accurately assess habitats' blue carbon potential; support a route for a blue carbon market to give economic value to ecosystem services; and pave the way for future opportunities to restore and conserve blue carbon habitats"[53];
- The **Collectif Algues Outre-Rade CA.OR,** based in Pays de Lorient, south Brittany, France, which focuses on growing, harvesting and using seaweeds for food[54];
- The **Dorset Coast Forum** and its aquaculture activities[55]. Based in UK, it was a partner in the Interreg IV A Two Seas project C-SCOPE (2009-2012), which produced an integrated MSP and Terrestrial Spatial Planning plan for Integrated Coastal Zone Management in UK and in Belgium[56]. It has produced the Dorset Mariculture Strategy 2020-2025 and has links to resources for investors in local aquaculture and farmers needing help in navigating licensing and permits and an interactive aquaculture map[57], as well as the regional ocean R&D cluster SWAN[58]. The Dorset Mariculture Strategy usefully lists the practical challenges that need to be

[50] https://algaebiomass.org/
[51] https://www.algae-uk.org.uk
[52] https://www.algae-uk.org.uk/projects
[53] https://www.ukbluecarbonforum.com
[54] https://www.linkedin.com/in/marie-line-théophile-34679276
[55] https://www.dorsetcoast.com/projects/aquaculture/
[56] http://www.cscope.eu/en/home/
[57] https://www.dorsetaquaculture.co.uk/
[58] https://maritimeuksw.org/

faced at local or regional level for aquacultural advancement (including algae and IMTA)[59], and could be a good model for other plans that need to integrate in-shore, off-shore and on-shore aspects.

- Denmark's **Havhøst** ('Ocean Harvest'), focused on regenerative ocean cultivation and engaging citizens to use blue areas in and around cities for local, sustainable food production, organising education and dissemination events & activities[60];
- **North Sea Farmers**[61], a consortium with c. 100 members, is focused on sustainable development of seaweed activities, carrying out joint investment projects in production, processing and value-chain verification. They have established an Offshore Test Site for operations projects, available to start-ups and companies scaling-up, in particular[62];
- The **Norwegian Seaweed Biorefinery Platform**[63], a project funded by The Research Council of Norway (2019-2024), is a national consortium aimed at harnessing the efforts of research institutions to produce new technologies for economically- and environmentally-sustainable seaweed biorefineries and models for value-chain analysis.

Regional groups include:

- The USA's **Long Island Sound Study**, which brings together the people and organisations needed to develop and deliver a Comprehensive Conservation and Management Plan for the Sound, including algae, IMTA and other developments[64];
- The USA's **Seaweed Hub**[65]**,** been funded by the Sea Grant Network, which could perhaps be monitored for ideas to bring into Europe, or collaborated with by joint conferences, when problems and opportunities are common and working together would help success;
- **SUBMARINER Network for Blue Growth**, constituted as a EEIG (European Economic Interest Grouping) and representing a very wide range of interests in the Baltic Region[66]. Since its foundation in 2013 it has it has developed into the leading transnational hub in Europe for promoting sustainable and innovative uses of marine resources, initiating 20 large-scale projects, value >€41 million, some of which are key to further development of algae, such as MUSES[67], underpinning Multi-Use developments at sea.
- **Greenwave,** a global network whose goal is to provide training, tools, and support to a baseline of 10,000 farmers by 2030 to catalyse the planting of regenerative ocean crops and yield meaningful economic and climate impacts.

Europe-wide groups and organisations include

- **EU4Algae**, the networking platform project funded by the EU (2022-2025), intended to become the major network driving forward the aims of the EU Algae Initiative. Launched in June 2022[68], it covers the breadth of algal interests, and already has about 600 members. It has been jointly established by DG MARE and the Climate, Infrastructure and Environment

[59] https://www.dorsetcoast.com/wp-content/uploads/2020/08/Dorset-Mariculture-Strategy-2020-2025_WEB-FINAL.pdf
[60] https://www.xn--havhst-eya.dk/in-english
[61] https://www.northseafarmers.org/
[62] https://www.northseafarmers.org/offshore-test-site
[63] https://www.linkedin.com/groups/8988723/ https://www.sintef.no/projectweb/seaweedplatform/
[64] https://longislandsoundstudy.net/
[65] https://seaweedhub.org/
[66] https://www.submariner-network.eu
[67] https://muses-project.com/
[68] https://www.facebook.com/hashtag/eu4algae

Agency (CINEA)[69]. EU4Algae is intended to underpin, facilitate and accelerate the scale-up of "a regenerative, resilient, fair and climate friendly algae industry in Europe"[70]. It is a platform for collaboration and networking among all types of European algae stakeholders, will be a single information hub on algae funding calls, projects, business-related information, intelligence and best practices and has already produced a strategy document for comment[71]. Another aim is to broaden the range of commercially-useful algae species in the EU. It has already established 7 working groups (WG) with active on-line workshops: WG1 Macroalgae Production; WG2 Microalgae Production; WG3 Algae for Food; WG4 Algae for Feed; WG5 Ecosystem Services/Bioremediation; WG6 Materials/Chemicals/Bioactives and Algae Biorefining; & WG7 Youth and Entrepreneurship. These are continuing to recruit interested members, to become prime movers in making the necessary changes in the European environment for algal activities;

- **EABA**, the European Algal Biomass Association, established as early as 2009, with 191 industrial, scientific and individual members and 14 observers, which has created 6 working groups dealing with algal products and applications for agriculture, aquaculture, cosmetics, food, organic applications and wastewater[72];
- **EuropaBio** and **EFIB**, the European Forum for Industrial Biotechnology, which have maintained an interest in algae as the sources of platform chemicals[73] and biofuels[74];
- **Seaweed for Europe**, aiming to accelerate sustainable seaweed industry and involving over 70 members ranging from seaweed farmers to processors, civil society, other networks, research institutions and banks[75]. It particularly addresses the specific needs of value-chains for targeted actions and has established six workstreams:
    - optimising seaweed farming licensing processes;
    - attracting public and private investors to the seaweed space;
    - creating a strong and collaborative stakeholder network;
    - establishing robust safety standards and a comprehensive certification system;
    - raising awareness on the benefits and potential of seaweed and;
    - leveraging science to accelerate innovation.

Facilities, biobanks and sources of accurate factual scientific data are vital resources to facilitate the growth of the algae-based Blue Bioeconomy to full industrial-scale production. Facilities may be web-based resources of high-quality data and knowledge to aid decisions on research, development and innovation topics. They can also be centres of knowledge, able to provide a range of services into the algae community including live samples and genomic data and training the workforce of the future. Many facilities have developed from academic or national research laboratories or have evolved as part of EU support, for example through SME programme, Regional Development or Framework/Horizon Programme funding. Specific engineering, technology and processing resources, demonstrators, are still mostly pilot-scale or small commercial scale. Opinion amongst those involved in algal research, development and innovation is that this scale is too small to provide appropriate data or models. As

[69] www.cinea.ec.europa.eu

[70] https://oceans-and-fisheries.ec.europa.eu/news/european-commission-launches-platform-promote-production-and-use-algae-europe-2022-02-09_en

[71] Issued to members for comment 1.12.2022

[72] https://www.eaba-association.org/en/working-groups

[73] https://www.europabio.org/europabio-comments-on-the-public-consultation-on-blue-bioeconomy/

[74] https://www.europabio.org/what-if-we-used-algae-to-make-biofuel/

[75] https://www.seaweedeurope.com

prefigured by the BBE Roadmap Forum and confirmed in the EU Algae Initiative, public funding of biorefineries and seaweed farming and harvesting is needed at a scale that can generate reliable and accurate data for LCA and econometric analysis that can then establish performance at full commercial scale and validate industrial and venture capital decisions to invest. Open-access pilot sites are also envisaged by the EU Algae Initiative, eg. Smart Pilots[76].

- AlgaeBase, providing foundation information on organisms for possible industrial culture[77];
- AlgaePARC[78] at Wageningen in the Netherlands, focused on all aspects of the microalgal production;
- Banco Español de Algos, the Spanish Algae Bank based in the Canary Islands[79];
- BBEU, the Bio Base Europe pilot plant at Ghent[80];
- BiOrbic Ireland, which includes algal topics in its bio-based industries programme[81];
- The Culture Collection of Algae and Protozoa CCAP, at SAMS in Scotland[82];
- EMODnet provides aggregated and graphical information on a wide range of marine activities and science[83]; a tool available on EMODNet is the European Atlas of the Seas[84], which can be interrogated to show microalgal production facilities;
- the UK MBA's MarLIN, Marine Life Information Network[85];
- MIRRI (Microbial Resource Research Infrastructure), which links culture collections, making organisms available for research and for industrial efforts, set up in 2010 as part of the European Strategy on Research Infrastructures[86];
- Norsk Planktonsenteret[87] and the Norwegian Seaweed Technology Centre[88], both active in projects spanning seeding to processing, involving sea and on-land cultivation and involving SINTEF and NTNU, the Science and Technology University; the Plankton centre operates with microalgae, zooplankton and seaweeds and is a partner in national and EU projects BioCycles, SafeKelp and SideStream;
- Pilots4U, which networks all existing pilots and demonstration facilities across Europe and provides a portal for identifying the most appropriate for needs[89];
- A Seaweed Academy, for training, skills development and information on all aspects of seaweed biology, production and processing[90];

[76] https://projects2014-2020.interregeurope.eu/smartpilots/
[77] https://www.algaebase.org/
[78] https://www.algaeparc.com/
[79] https://marinebiotechnology.org/en/
[80] https://www.bbeu.org/
[81] https://biorbic.com/
[82] https://www.sams.ac.uk/facilities/ccap/
[83] https://emodnet.ec.europa.eu/en
[84] https://ec.europa.eu/maritimeaffairs/atlas/maritime_atlas
[85] https://www.marlin.ac.uk/
[86] https://www.mirri.org/
[87] https://www.planktonsenteret.no/
[88] https://www.sintef.no/en/ocean/initiatives/norwegian-seaweed-technology-center/
[89] https://biopilots4u.eu/about
[90] https://seaweedacademy.co.uk/

- TNO's Seaweed Processing Facility at Petten, in the Netherlands, opened in September 2018[91], covering processing of the entire chain from wet biomass to end-products, at pilot-scale;
- And, outside Europe, a good example is the California Centre for Algae Biotechnology[92], (Cal-CAB) networking researchers from around the state with the private sector to develop algae as a commercially viable feedstock for biofuels, green chemicals, nutraceuticals, feeds, and other high value bio-products, and providing algae growth systems at pre-commercial scale, including 9,600 litres of plastic bag PBRs, 18 outdoor 1,000 litre mini-ponds, two 30-ft 8,000 litre raceway ponds, a harvesting station with four 900 litre conical tanks and support facilities.

1.5 Value chains, eco-services

The potential value-chains of outputs from algae are very diverse. Some, such as the marine hydrocolloids industry, are the longest-established and will be more wedded to conventional, well-tried supply-chain and processing procedures. Others, such as eco-services, bioplastics, biochar, and alternatives to plant- and plastic-fibre clothing are beginning to be realised. Thierry Chopin describes the broad range of possible outputs from algal biorefineries:

> One can produce on one hand a range of bio-based, high-value compounds, such as food and feed products, ingredients and supplements, protein substitutes for aquaculture feed, phycocolloids, fertilisers, biostimulants, pharmaceuticals, cosmetics, nutraceuticals, botanicals, pigments and biomaterials. And on the other hand produce lower-value commodity energy compounds such as biofuels, biodiesels, gasoline, waxes, olefins, biogases and bioalcohols.
>
> *Source Chopin T in Holmyard N (2022)* [93]

The greatest need is seen to be to turn extraction of high-value components into a reality, to extract them and get them to the market and to grow market expectations in step with production development. There is plenty of innovation in the EU Green Deal programme and associated support mechanisms, but it is difficult to find attention to the value chain or growing consumer interest in algal products.

The diversity of targets that could be developed using algal bioresources include:

- The UK **Centre for Innovation Excellence in Livestock's** offer of funds from InnovateUK to explore the impacts of seaweeds in the diet on methane-producing livestock and develop maps for seaweed product value-chains[94];
- A suite of publications from the **Macroalgal Fibre Initiative Ireland** showing that seaweed extracts rich in laminarins (65%), fucoidans and other bioactives have prebiotic and immunomodulatory effects on piglet and chicken gastrointestinal tracts, resulting in improved

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91 https://www.tno.nl/en/technology-science/labs/seaweed-lab,

92 https://algae.ucsd.edu/

93 https://thefishsite.com/articles/seaweed-aquaculture-panacea-or-hype-imta N Holmyard 6.4.22

94 https://cielivestock.co.uk/seed-funding-aquaculture/

live weight gains[95,96,97], evidence of reduced shedding of Salmonella-shedding[98];with the seaweeds used included *Laminaria hyperborea* (for laminarin), and *Sargassum* or *Ascophyllum* (for fucoidan);

- a USA start-up **Minus Materials**[99] with biogenic limestone developed from a cultivatable coccolithophore microalga that contains enough calcium to substitute for mineral limestone in cement, based on research funded by the US DOE's ARPA-E program[100]; the company aims to produce 25-50 tons/acre/year of biogenic limestone and estimates the large-scale potential as >250 million tonnes of CO_2 removed from the environment in addition to a substantial reduction in the 2 gigatonnes of CO_2 produced world-wide each year by cement manufacture; residual biomass will be used for chemical, cosmetic, food ingredient or biofuel production;
- Efforts to link algae producers and customers in a new way such as the on-line platform **Place des algues**, offering dried *Asparagopsis* at €1700/kg or powdered *Ascophyllum nodosum* at €7/kg[101];
- A new EU project, **SeaMark** (Seaweed-Based Market Applications 2022-2026)[102] aimed at 12 different value-chains based on *Saccharina latissima*, including bio-packaging, meat-replacers, nutraceuticals, medical devices and animal feed supplements; SeaMark will also quantify the ecosystem services provided by large-scale seaweed cultivation as a bioremediation tool and key element of the new circular bioeconomy, working in the Faroe Islands and off the Brittany coast in France;
- An Algae-UK BIV (Business Innovation Voucher) project, **SEADYES**, a collaboration between SAMS and the Scottish textiles company Crùbag to create new sustainable dyes from local seaweeds including *Palmaria* and *Ceramium* (red), *Alaria* and *Laminaria* (brown) and *Ulva* (green), to begin to replace the estimated c. 140,000 tonnes of synthetic dyes that become environmental pollutants during textile manufacture and disposal[103].

There is currently a strong focus on seaweed-based packaging and solid-form bio-plastics, which is attracting investment[104]; this is also driving processing technologies from conventional chemicals and heat toward extraction of polysaccharides by fermentation under less harsh conditions, allowing use of the residual biomass for, e.g., animal feed. Emergent companies are often in collaboration with major names, aiding consumer acceptance. However, the companies are still young (Evoware the oldest, founded in 2016) and dependent on investment rounds to get to full scale. Examples include:

[95] O'Doherty JV, Venardou B et al. (2021) Feeding Marine Polysaccharides to Alleviate the Negative Effects Associated with Weaning in Pigs Animals 11: 2644 doi: 10.3390/ ani11092644

[96] Rattigan R, Sweeney T et al. (2020) Laminarin-rich extract improves growth performance, small intestinal morphology, gene expression of nutrient transporters and the large intestinal microbial composition of piglets during the critical post-weaning period Br J Nutrit (2020), 123, 255–263 doi: 10.1017/S0007114519002678

[97] Venardou B, O'Doherty JV et al. (2021) Effects of dietary supplementation with a laminarin-rich extract on the growth performance and gastrointestinal health in broilers Poultry Science 100: 101179 doi: 10.1016/j.psj.2021.101179

[98] Venardou B, O'Doherty JV et al. (2022) Potential of a fucoidan-rich Ascophyllum nodosum extract to reduce Salmonella shedding and improve gastrointestinal health in weaned pigs naturally infected with Salmonella J An Sci Biotech 13:39 doi: 10.1186/s40104-022-00685-4

[99] https://www.minusmaterials.com/

[100] https://www.colorado.edu/today/2022/06/23/cities-future-may-be-built-algae-grown-limestone

[101] https://placedesalgues.fr/en/

[102] https://www.linkedin.com/company/seamarkeu/

[103] https://www.algae-uk.org.uk/projects/biv-round-2-seadyes-use-of-seaweed-as-a-sustainable-feedstock-for-dye-extraction-and-application-in-the-textile-industry-screening-extraction-and-dyeing/

[104] Seaweed-based Packaging Food and Nutrition Feb 24, 2022 https://www.futurebridge.com/seaweed-based-packaging/

- **Evoware**[105], whose bioplastic is made from indigenous red seaweeds bought from local farmers to replace the plastic food containers and packaging that have made Indonesia the world's second-largest contributor to ocean pollution; certified halal, the product range includes cups, sauce and coffee sachets, burger wraps and packaging for straws, sanitary napkins, soaps, and toothpicks;
- **Loliware**[106]**,** making edible cups from agar and natural flavours of cherry, grapefruit and vanilla, and edible straws; the process involves the use of water, sugar, calcium chloride and citric acid, with optional additional pectin, vegetable glycerin or agar, all food-accepted components;
- **Notpla**[107], a UK start-up, which had received seed-funding of almost €13 million by December 2021 to turn commercial hydrocolloids from brown seaweeds such as kelp into Ooho!, its edible, compostable packaging for liquids and solids. Notpla collaborated with Lucozade on edible sports drink balls for marathon runners and with Glenlivet for whisky balls in London Cocktail Week and has developed further packaging forms including coating for plastic packs, oil pipettes for restaurants and home food, hot-water and cold-water sachets for coffee, tea, sauces such as Heinz ketchup and takeaway boxes for the Just Eat company; it plans to develop a paper containing seaweed fibre and to organise end-customer leasing schemes for its packaging manufacturing systems. In December 2022, Notpla won Earthshot's Waste-Free World prize[108], worth $1 million;
- **Sway**[109] received funding of about $2.5 million in a seed round led by Starbucks' Valor Siren Ventures for developing bags during 2022 and trialling them in 2023; the seaweed-derived material is stronger than the conventional LDPE used for packaging film and bags, are coloured using seaweed extracts, and are compostable, acting as a soil improver.

Eco-services build on the ability of microalgae and microalgae to remove macronutrients like N & P and CO_2 from the environment and from wastewater streams. To stimulate this, it will be necessary to have a greater understanding of algal system impacts. For example, the UK **Centre for Innovation Excellence in Livestock** is offering funding from InnovateUK to increase the understanding of Life Cycle Assessment (LCA) and Blue Carbon within the aquaculture sector, including line-grown seaweeds[110]. It is also seen as crucial to extend Carbon Credit schemes to this kind of activity and ideally set up new types of scheme, such as Thierry Chopin's Nutrient Trading Credits[111].

It is undeniable that algae are extremely efficient at removing CO_2, nitrates and phosphorus and incorporating them into their own utilisable content. The most effective and shortest-chain Circularity actions are to eat them as food or feed or convert the wet biomass to energy. Energy-focused end-products may be liquid bio-oils, bio-gas, or biochars. Processes that lead to biochar result in re-cycling of energy content and locking-up of carbon in soil when biochar is used as an improver. The latter may be a surprisingly-feasible output for farmed and wild-collected seaweeds, and for microalgal biomass, provided that undesirable heavy metals and other substances don't then accumulate in soils and crops.

105 See https://www.webpackaging.com/en/portals/evoware/

106 https://www.loliware.com/

107 https://www.notpla.com/

108 https://earthshotprize.org/

109 https://swaythefuture.com/

110 https://cielivestock.co.uk/seed-funding-aquaculture/

111 https://aquafeed.co.uk/entrada/the-interview-thierry-chopin-professor-of-marine-biology-university-of-new-brunswick-director-seaweed-and-integrated-multi-trophic-aquaculture-research-laboratory-president-of-chopin-coastal-health-solutions-inc.-22379

- The UK-based start-up **Carbon Kapture**[112] plans to open 50 kelp farms on the south coast and in south Wales to capture CO_2 and produce biochar, hoping to start with one farm in north-west Wales in 2022 and end by having "1 million metres of seaweed ropes in the water by the end of 2023";
- Tasmania-based **Southern Ocean Carbon Company** wants to set up multiple kelp-sites round Southern Tasmania and plans to achieve seaweed-based Blue Carbon Credits worth A$100 million (€64 million) by 2027-2029. Whether these large goals are achievable should be watched-for;
- Carbon absorption at-scale is a focus of projects and business start-ups that aim to establish ocean seaweed-farming or harvesting to trap and sink CO_2, and the Great Atlantic Sargassum Belt, first seen on satellite in 2011 and almost 9,000 km long, is the focus of efforts by more than one company:
    - **Seafields**[113] plans a floating deep-water seaweed farm of 55,000 sq km "the size of Croatia", projected to remove 1 billion tonnes of CO_2 a year from the atmosphere (2% of annual human production)[114]. The concept will be tested in the Caribbean and Mexico during 2023, using nutrients piped up from the cooler deeper water underlying the ocean levels that trap *Sargassum*. Floating balers will sink compressed seaweed blocks down to the ocean floor, where there is so little oxygen it's proposed that the bales will not rot and the contained carbon will persist inert for hundreds if not thousands of years. The company plans to sell credits for captured carbon on the world's carbon markets. With this approach, there are concerns about the size of operations needed to make even a tiny impact in rebalancing anthropogenic carbon emissions; the potential impacts on environment and biodiversity will also be very difficult to assess and monitor at all appropriate sea levels without rapid advancement of and heavy investment in autonomous systems;
    - **Seaweed Generation**[115], based in the UK, is developing a robotic collector initially for rounding-up floating seaweed and in future for harvesting from ocean farms using robotic technologies; the initial impetus was the problem of nuisance *Sargassum*, beach-wracked and rotting, but the potential for collecting and sinking seaweed from the Great Atlantic Sargassum Belt has driven the company forward, aiming to deal with 100 million tonnes of kelp;
    - the US company **Running Tide** is already putting 'carbon buoys' into sites round the world's oceans; these contain forestry residues and limestone, are seeded with kelp and sink after 3 months' growth to below 1000 m depth[116]. The company aims to scale up over ten years to sequester 1 billion tonnes of carbon.

As mentioned in § 1.6.1.2 below, there is still a role for seaweeds in IMTA, especially for shellfish co-culture, and China is the good model here. Using *Saccharina japonica* in IMTA with scallop-farming in areas such as Hanggou Bay was instrumental in reducing water pollutants such as CO_2, heavy metals and inorganic wastes and had 67% higher economic benefits than kelp monoculture and 92% higher than scallop monoculture[117]. There is also increasing and intriguing evidence that seaweeds may protect

[112] https://www.carbonkapture.org/

[113] www.seafields.eco

[114] https://www.bbc.co.uk/news/science-environment-63200589 16.10.22

[115] https://www.seaweedgeneration.com/

[116] https://www.runningtide.com/science

[117] Hu Z-M, Shan T-F et al. (2021) Kelp aquaculture in China: a retrospective and future prospect Rev Aquac 13: 1324–1351 doi: 10.1111

other aquaculture crops from contamination by toxic microalgae by absorbing nutrients more efficiently, in effect starving them.

Regenerative Ocean Farming is a concept that sets IMTA in a more natural setting, seeking to re-wild maritime areas and re-balance the environment and ocean nutrient fluxes. **GreenWave** is an advocacy organisation that also trains seaweed and shellfish farmers, with a 10-year aim of encouraging 10,000 farms covering 1 million acres of ocean[118]; it also has its own *Saccharina* farm and seed-production unit and is involved in projects from induced sporulation of kelp and selection for resilience, through establishing the carbon-offset credentials for farms and the functional impacts of kelp fertilisers on nitrogenous land emissions, to the impacts of re-forestation and the development of advanced sensor technologies[119]. At the other end of the scale are local groups like **Havhøst** and the **Dorset Coast Forum** in UK (see Networks section), providing support for smaller-scale integrated restoration of eco-balance.

For bioenergy, the potential of microalgae and seaweeds is large. ETIP Bioenergy provides a list of EU projects to 2019 and a contemporary list of demonstration plants[120], noting funding of €20.5 million in the 2010 Framework Programme 7 call; the Q&A on the EU Algae Initiative[121] states that Horizon 2020 programme funded 116 algal projects at a cost of €273 million, some of which are bioenergy-related.

1.6 Technology status and advances

1.6.1 Algae biology, production, harvesting

Genomics, involving the understanding of seaweed and microalgal genomes, genetic characterisation, knowledge of how genes determine metabolism and productivity and the interactions of genes with the environment, is crucial to further productive development of algal opportunities in a sustainable way. There is also increasing focus on the aspects of interactions with the organisms found on or in close proximity to algae, in biofilms, as consortia or as part of the surface or internal microbiome, and the gene-talk between members of consortia that might be manipulated within bioreactors for bioprocessing efficiencies. The science of microbiomics indeed began with studies of the on-board microbes in marine sponges, in the 1990s and microbiome inoculation is being used for coral reef remediation in Australia and the Arabian Sea. The relative roles of environment and genes in generating desirable characteristics and components need assessing for each situation, which implies much more sensitive and specific predictors are needed.

The scale of seaweed nurseries and microalgal starter production units is still a limitation and will need to be addressed for increases in biomass of the sizes predicted.

For microalgal cultivation, the two systems in commonest use are open-pond/raceway and closed bioreactors. Conventional thinking on open ponds is lower capital outlay but less-controllable growing conditions, nutrient inputs and contamination hazards. Scale-up here requires very close attention to water recycling, aeration, improvement of the ability to separate contaminating organisms from algal biomass or at least the ability to manage them using cultivation conditions. Closed bioreactors benefit from controlled environment with managed growth conditions, disease exclusion and elimination of environmental cross-contamination but have high capital and running costs. They do however allow

[118] https://www.greenwave.org/

[119] https://www.greenwave.org/our-farm

[120] https://www.etipbioenergy.eu/value-chains/feedstocks/algae-and-aquatic-biomass/algae-funded-projects & https://www.etipbioenergy.eu/value-chains/feedstocks/algae-and-aquatic-biomass/algae-demoplants

[121] https://ec.europa.eu/commission/presscorner/detail/en/qanda_22_690

use of CO_2 from the air by direct capture or as circularity outputs of industry, power plants, anaerobic digesters and soluble carbonates, and integration with nutrient-rich outflows. For closed bioreactors, the conventional organisms are photosynthetic microalgae or cyanobacteria, entirely dependent on light (photoautotrophic), or heterotrophic species, lacking in chlorophyll and requiring external sources of nitrogen and organic carbon. Photobioreactor (PBR) arrays (PBRs) are available that can manage total volumes of 400,000 L, and operate on a continuous or semi-continuous harvesting programme using filtration systems. Problems endemic to photoautotrophic systems include suppression by over-intense light, biofilm formation on photobioreactor surfaces so the microalgal growth blocks its own light source, and the need for O_2 removal. In the interests of scale-up, the trend is to use heterotrophs, or mixotrophic organisms which can photosynthesise or metabolise organic carbon, as heterotrophs and mixotrophs produce hundreds of times the biomass of phototrophs per litre, the bioreactors for these have a lower footprint than large-scale PBRs and they are easier to integrate with external process outflows[122].

Conventional farming of seaweed is near-shore or in easily-accessible offshore sites on longlines; wild seaweed is harvested close to shore or as beach-wrack. The barriers to near-coast cultivation scale-up include nutrient limitation and thermal stress that reduce the growing season, and competition with other marine and coastal uses, especially in near-shore waters, sheltered bays, lochs and estuaries. Off-shore, conventional longline infrastructure does not cope well with strong current and wave conditions and is not deemed financially viable at scale as it is capital intensive, requires extended hatchery incubation times, is inefficient to deploy and recover and the space and harvest-manoeuvring required for seaweed longlines continue to conflict with other marine activity such as wind-farms. The challenge is to provide the infrastructure to take account of seaweed's adaptations for growing well in open water with strong currents and cooler temperatures[123].

For both microalgae and seaweeds there is a need for soluble nitrogen (urea, nitrate or ammonium) and phosphorus. State of the art is turning towards integration of microalgal facilities with sources of relatively nutrient-rich outflows, such as those from food and feed industries, dairy and brewing, wood- and paper-processing, sewage processing and anaerobic digestion of biowastes, to avoid the costs of nutrient supplementation. Availability of CO_2 from the same sources is a bonus, and anaerobic digesters will provide this as well as heat in winter. This trend also favours modular systems[124], and is being increasingly explored for on-land seaweed farming.

For farmed seaweeds, integration with other aquaculture activities in-sea, better and more automated mapping of nutrient distribution, including offshore human and agricultural out-falls, to aid siting, and on-land integration with aquaculture, horticulture or food-processing outflows will be necessary. For open-water and oceanic harvesting, it may be necessary to create nutrient upwelling from deeper waters to the surface layers, which may be easier to do in multi-use Wind+Weed settings, where engineered access to the seabed might exist, than in floating farms.

As seaweed farming moves further out to sea, the profile of culture substrates is expanding beyond longline ropes to include flat matrices, favouring gel-based seeding strip technology and assisting non-linear structures such as rings, grids, ladders and single-point fixation. Remote monitoring becomes far more important, a key element in Aquaculture 4.0:

- integrated satellite remote sensing
- field surveys

[122] Pierobon SC, Cheng X et al. (2018) Emerging microalgae technology: a review Sustain Energy Fuels 2: 13 doi: 10.1039/c7se00236j

[123] Adapted from SeaGrown's aplication to the UK Biomass Feedstocks Innovation Programme, see https://www.gov.uk/government/publications/biomass-feedstocks-innovation-programme-successful-projects

[124] Pierobon SC, Cheng X et al. (2018) Emerging microalgae technology: a review Sustain Energy Fuels 2: 13 doi: 10.1039/c7se00236j

- GIS-based models to monitor the six main environmental parameters (light intensity, water temperature, velocity, inorganic nitrogen, salinity and depth)
- oceanographic characteristics such as degree of spatial variability in coastal pH and nutrient conditions, seasonal surface temperatures, suspended solids, sea surface nitrate, bathymetry and slope.

An important aspect here is to develop **a single-portal, ideally open-access, aggregation database of oceanographic information** of the type that will better enable decisions on siting to be made and licences and permits to be issued quickly. **EMODnet** is possibly the current best model for this, for example in its bathymetry section[125]. It is possible to piece together information that can incompletely inform planning and siting decisions, such as fisheries maps, protected areas maps, navigation charts or national surveys, but the type of information needed for fully-informed decisions goes far beyond this, including benthic surveys for sediment types, benthometry for seabed profiling, nutrient dynamics maps. **NOAA** in USA provides NOAA OceanReports[126], giving summary statistics and infographics for six main topics: general information, energy and minerals, natural resources and conservation, oceanographic and biophysical, transportation and infrastructure, and economics and commerce, for US waters, easily available only to US establishments. Chile also has maps for existing permits. The results of the **Nippon Foundation- GEBCO Seabed 2030 Project**[127] may also be useful – it was launched February 2018 with the objective of establishing worldwide collaborations to map the entire seabed by 2030.

Harvesting from microalgal production units is technologically well-advanced for PBR and closed-vessel systems, increasingly carried out on a continuous or semi-continuous basis, using membrane filtration and/or flocculation in separate collecting units. For open ponds and raceways, improvements are still needed for separation, sedimentation and flocculation in retention areas from which liquids are returned into the system. Improvements here will require more automation and more techniques for cost-effective de-watering. Harvesting from in-sea seaweed farms requires collection boats or ships that can manoeuvre close enough to lines or substrate structures to avoid fouling, collisions or unwanted line-cutting, and the biggest advances here will be in specialised modular 'drop-in, pull-out' handling gear units on boats, and in autonomous monitoring and harvesting equipment.

1.6.1.1 Microalgae

Genomics tools will aid breeding programmes to identify target traits in microalgae and select strains for industrial use, especially where there is pressure to identify and use productive indigenous species:

- The EU-funded **NewTechAqua**[128] project (2020-2023), part of the Horizon 2020 programme "Sustainable European aquaculture 4.0: nutrition and breeding", intends to use "strain selection and setup of the base population of the breeding programme, definition of the optimal breeding goal, recording methods for the breeding goal traits by molecular and flow cytometry techniques, testing and design optimal selection strategies". This involves the Banco Español de Algas in the Canary Islands, which is looking for novel sexually-reproductive microalgae to avoid GM tools. After screening more than 30 wild isolates from 8 species, BEA has succeeded in establishing cultures of a newly-found isolate of *Seminavis robusta*, an inhabitant of biofilms in coastal and tidal shallows, and is scaling up for biomass characterisation. This brings together three strands of current advances – novel organisms, local organisms and biofilm-formers;

[125] https://emodnet.ec.europa.eu/en/bathymetry
[126] https://coast.noaa.gov/digitalcoast/tools/ort.html
[127] https://seabed2030.org/
[128] https://www.newtechaqua.eu/

- **KAUST**, in Saudi Arabia, is also looking for indigenous strains of *Nannochloropsis* and *Spirulina* to replace commercially-available foreign strain for use in its new open-pond and PBR programme[129].

Pierobon *et al*. (2018)[130] review the technologies that will make microalgal cultivation more efficient and effective:

- Flat panel PBRs for greatest biomass productivities and photosynthetic efficiencies;
- Conversion of solar radiation to green light for higher densities;
- Use of open-pore glass sponges or externally powered wireless LEDs in suspension to counteract density-based light limitation;
- Matching supply of dissolved carbon with culture demand by on-demand CO_2 injection, improving absorption efficiency to up to 96% compared with continuous aeration;
- Using microbubbling technologies such as fluidic oscillation or pulse-pressure on microporous membranes to aid CO_2 saturation, transfer and uptake;
- Using transparent nanoporous materials to reduce mass-transfer barriers for CO_2 and O_2, enhance internal light transmission and act as internal waveguides in scalable reactor designs;
- Making use of biofilms in Porous Substrate Bioreactors, in which printing paper or solid or fibrous natural or synthetic polymers as substrata produce consistent superior productivity and light utilisation efficiencies compared to conventional PBRs.

In addition, mutual symbiosis between multiple immobilised species can also benefit nutrient extraction and production and the consortium bioreactor may well become a target for the future, especially if the different organisms can simultaneously generate inputs into different value-chains.

Occasionally, extremely innovative technologies for microalgal growth arise, e.g. the result of a collaboration between ETH, the Swiss Federal Institute of Technology in Zurich, the Singapore-ETH Collaboration Centre and the processing technology company Bühler, based on ETH-Zurich's discovery of the power of nanosecond pulsed electric fields to stimulate microalgal growth[131]. This is embedded in Bühler's Stellar Gemini system and has produced an average 17% growth and yield improvement over conventional systems. The aim is to generate sustainable single-cell protein production modules for urban environments, with new foods as outputs[132].

Disease identification and control is vital for all algal systems. Because of farm density, reliance on a limited number of strains and environmental conditions of farming, China can experience loss of more than 50% of its cultivated seaweed crop due to disease. With respect to kelp in Europe, the water conditions even close to shore are different from China's and the industry has not reached a size where disease is a pressing topic. Conventional identification is visual, and treatment may be impossible due to environmental or food-safety impacts of potential pesticides or inherent design features of the systems. US DOE's **BETO** (Bioenergy Technologies Office) held a workshop in April 2021[133] on control of diseases that limit microalgal farming, concluding that lack of knowledge and ability to monitor and manage algal cultivation effectively was a major barrier to increasing scale, especially in the context of open-pond microalgal growth. Filtration will not remove viruses, fungi and chytrids and re-circulation

[129] https://www.kaust.edu.sa/en/news/the-future-of-algae-a-treasure-trove-of-green-for-the-kingdom

[130] Pierobon SC, Cheng X *et al*. (2018) Emerging microalgae technology: a review *Sustain Energy Fuels* 2: 13 doi: 10.1039/c7se00236j:

[131] https://sfp.ethz.ch/research/PEF-research.html

[132] https://www.buhlergroup.com/content/buhlergroup/global/en/media/media-releases/sec_s_microalgaeprojectgetsastellaradditionfromitspartnerbuehler.html

[133] https://www.energy.gov/eere/bioenergy/events/barriers-scale-algae-crop-protection-workshop

means that grazers such as flagellates and rotifers are constantly returned to fresh inputs of microalgae. A target is to introduce community engineering of organisms to reduce the severity of grazing and parasitism, in a microbiomic or probiotic concept. Management of dissolved O_2 level and control of water temperatures are important tools in fighting pests, as are design elements such as pumps instead of paddle wheels. Environmental DNA sampling as part of monitoring will give early warning of pathogen attack and success of treatment or management. For open-pond microalgae, a novel field-use chemical ionisation mass spectroscope is in process of commercialisation by **Thermo Fisher Scientific**[134]. Developed at **UCal San Diego**, this detects changes in algal health and build-up of unwanted organisms such as grazers several days before problems are detectable to the naked eye, by 'sniffing' volatiles signatures in the water and air above the pond.

Harvesting of microalgae to boost biomass content is carried out using screening (microstrainers or vibrating screens), which can be done on a semi-continuous basis, sedimentation (flocculation or ultra-sound), where the concentration is increased from 0.1% of total suspended solids (TSS) to a slurry of about 2–7% TSS, air flotation and the emerging tool of electric field assisted harvesting. Harvesting is estimated to cost about 30% of the total biomass cost. For further concentration (thickening), centrifugation or membrane separation and filtration save energy costs compared to drying but require capital investment, with disproportionate increases in energy costs as target concentrations increase. Further removal of water (dehydration) is achieved by solar drying, spray drying, rotary evaporator, freeze drying and belt drying – solar drying is inconsistent, the others are energy-intensive, though reduce the water content dramatically, eg freeze-drying from >85% to <10%; newer processes use electrostatic spray-drying to avoid denaturing outputs when they are high-value[135].

Flocculation is a relatively inexpensive method of aggregating microalgae to make it easier to remove water, often by membrane separation or filtration rather than energy-expensive centrifugation; chemical flocculants such as aluminium salts may be used but natural chitin from crustacean shells appears a more circular choice and can be shown to have high flocculation effectiveness, even with consortia of wild microalgae[136], lower cost (up to 30% reported) and lower impact on downstream products.

1.6.1.2 Seaweeds

Europe could definitely look to China for answers to gaps and challenges in seaweed farming and IMTA, and incorporate their strategies and practical actions into RTI-support programmes and research and farming practice. In genomics, these include[137]:

- establishing platforms for high-throughput genotyping
- acquiring highly contiguous and complete kelp genome sequences, for full annotation
- anchoring the genome sequences to genetic maps, identifying QTLs for biosynthesis, performance and production
- establishing high-throughput cryopreservation protocols and pathways for kelp gametophytes and sporophytes
- setting up seaweed germplasm banks and microalgal cell banks to safeguard local diversity and be the basis for genomic, metagenomic and metabolomic studies

[134] https://www.energy.gov/sites/default/files/2021-11/beto-algae-workshop-report-nov-2021.pdf

[135] Pierobon SC, Cheng X et al. (2018) Emerging microalgae technology: a review Sustain Energy Fuels 2: 13 doi: 10.1039/c7se00236j

[136] Acosta-Ferreira S, Castillo OS et al. (2020) Production and physicochemical characterisation of chitosan for the harvesting of wild microalgae consortia Biotechnol Rep 28:e00554

[137] Hu Z-M, Shan T-F et al. (2021) Kelp aquaculture in China: a retrospective and future prospect Rev Aquac 13: 1324–1351 doi: 10.1111/raq

- working on the kelp holobiome, as the balance between kelp and their microbiome is important for temperature-tolerance, growth, proportions of constituents, seasonal variations and productivity.

In operational terms, for seaweed farming four fundamental bottlenecks in increasing biomass production to commercial scale have been identified, all of which are susceptible to technological advancement for cost-reduction and increased efficiency and are the subject of continuing action:

- streamlined and consistent production of seaweed seeds;
- capital costs for in-water rigging;
- efficient seeding and deployment of growing lines, which is currently manual, therefore labour-intensive, and weather-dependent; and
- efficient harvesting boats and harvesting technologies for cultivated seaweed[138].

To help this, the EU and Member States have supported and continue to fund projects and researcher mobility to move knowledge forward, such as:

- **ASPIRE** (2022-2024)[139], establishing a collection of high-yielding *Palmaria* seaweed for farmed cultivation using a full range of genetic tools including high-throughput genotyping and phenotyping, next generation sequencing, bioinformatics, performance screening (growth, morphology characteristics and photosynthetic parameters) and metabolomic analysis (primary/secondary metabolites using GC-MS, spectrophotometer, NMR);
- **IDEALG**, funded in France, which included investigation of seaweed microbiomes[140];
- a **Network of Excellence in Marine Genomics** almost 20 years ago (2004-2008)[141];
- **SeaMark** (2022-2026)[142], aimed at scaling-up ocean seaweed farming and on-land seaweed IMTA, using selective breeding technologies within EU seaweed crop genetics to increase biomass yield;
- The **Seaweed Research Group at University of Gothenburg** is identifying and selecting high-growth, high-crude protein strains of indigenous *Ulva fenestrata* using 'DNA barcoding' to characterise strains, growing on-land using effluent from industrial seaweed processing for nutrient reclamation and bioremediation, followed by protein extraction[143]. Although the process is still at bench-scale, homogenisation of a high-protein isolate, alkaline extraction, acid-precipitation and drying, with intervening centrifugation, has produced a powder with 60% protein content, from a 20% start;
- The **Swedish Mariculture Centre** University of Gothenburg has mapped local green and red seaweed species to assess them for cultivability and industrial potential in the Sweaweed project 2015-2020, in a 2 hectare rope farm[144].

Another barrier to full sustainable, circular use of seaweeds is that only eight genera provide 96.4% of the world production: *Saccharina* (kombu), 35.4%, *Eucheuma/Kappaphycus*, 33.6%, *Gracilaria*, 10.5%,

[138] By SeaGrown in a UK BEIS Biomass Innovation project; the final report is available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1089674/Phase_1_report_-_SeaGrown_Limited_-_Transforming_UK_offshore_marine_algae_biomass_production.pdf

[139] https://cordis.europa.eu/project/id/101066815

[140] https://www.idealg.org/

[141] https://cordis.europa.eu/project/id/505403

[142] https://cordis.europa.eu/project/id/101060379

[143] https://www.gu.se/en/swemarc-marine-aqauculture/research/ongoing-projects

[144] https://www.gu.se/en/swemarc-marine-aqauculture/research/ongoing-projects

Porphyra and *Pyropia* (nori), 8.6%, *Undaria* (wakame), 7.4% and *Sargassum*, 0.9%. Bringing new species of seaweeds into productive cultivation is coming forward as a concern and as an opportunity, with respect to the need for new species to generate anticipated quantities for commitment to a blue circular economy, and the prospect of new bioactives, new uses and new value-chains. Green seaweeds account for just over 1 percent of global landings and are seen as an untapped biological resource[145]. *Ulva*, Sea Lettuce, is possibly the best-recognised species and is being used in IMTA and biorefinery, at-sea and on-land.

Challenges for off-shore seaweed production include supply of nutrients and assurance that toxic microalgae are not present. Challenges for seaweed processing begin at the harvesting stage. Technological responses include semi-automation or complete automation of lifting, cutting and depositing in boats and designing and building seeding and harvesting vessels with kit that can be 'plugged-in' to a multi-purpose infrastructure, allowing alternative uses for the rest of the year, as in SINTEF's project below.

Examples of focus on the infrastructure and engineering of production and harvesting include:

- the special vessel designed and built by Alginor's harvesting subsidiary **Hypomar**, the Inceptor, that can harvest up to 3,000 tonnes of *Laminaria hyperborea* per year[146];
- **North Sea Farmers**, the Dutch consortium, has successfully deployed an automated lifting, cutting and bagging system at a test site 12 km off-shore and has also designed an improved fixing system, the Eco-Anchor[147];
- The Indian company **Sea6 Energy**, producing seaweeds off-shore in Indonesia using a SeaCombine catamaran-style seeding and harvesting platform with horizontal ropelines for cultivation[148];
- 'Transforming UK offshore marine algae biomass production', led by **SeaGrown**[149], one of the **UK Biomass Feedstocks Innovation Programme** (BFIP) projects[150]. BFIP funded 25 projects in Phase 1, total £4M and 12 follow-ons in Phase 2, with total funding of £32M, of which this is one, aimed at creating a prototype offshore seeding and harvesting system. The Fully Automated, Transportable, Holistic Offshore Macroalgae System (FATHOMS) is for longline seaweed farming, using specially-designed deck machinery tailored to a new-design growing rig in the water, and is projected to save >45% in capital costs and >60% in running costs for operation of a 40,000m offshore seaweed farm. Scarborough-based SeaGrown already has a seaweed hatchery and a 25-hectare offshore seaweed farm in the North Sea off the UK's Yorkshire Coast, with a first harvest of cultivated seaweed in Summer 2021;
- work at the Woods Hole Oceanographic Institution funded by the Pacific States Marine Fisheries Commission, for an automated underwater seaweed seed-string deployment device[151], which won the Seagriculture Silver Award in October 2022; it carries two seed-spools and can be deployed like a knitting machine from one end of a grow-line to the other, to be detached by quick-connect clips and moved manually to the next line for reattachment and automated seeding return, deploying multiple units at the same time to further increase efficiency of the

145 Moreira A, Cruz S *et al.* (2021) The underexplored potential of green algae in aquaculture *Rev Aquac* doi: 10.1111/raq.12580

146 https://alginor.no/about-us/our-raw-material/

147 https://www.northseafarmers.org/projects/eco-anchor

148 https://www.sea6energy.com/automated-farming

149 https://www.seagrown.co.uk

150 https://www.gov.uk/government/publications/apply-for-the-biomass-feedstocks-innovation-programme

151 https://www.whoi.edu/press-room/news-release/woods-hole-oceanographic-institution-receives-seagriculture-innovation-awards/

seeding process. It eliminates the need for grow-line attachment and detachment, allowing faster seeding time, better integrity of seeding spools and fewer boat trips;

- dealing with seasonality and the narrow harvesting window, the EU project **Macrofuels** (2016-2019)[152] extended the growing season during its trials using crop rotation of native, highly productive brown, red and green seaweeds grown on advanced textile substrates with an anticipated harvest of 25 kg seaweeds (wet weight) per m^2 per year harvested at $1000m^2$/hr all year round;
- **SINTEF Norway's Seaweed Cultivation Vessel 2020** project[153]; in this, three concepts were developed, two based on existing fish-farm service vessels or seaweed harvesters, for in-shore work, and one a new design for off-shore farms. For each concept, the harvesting-, handling-, storing and preservation equipment was modular, to allow for alternative use of the vessels in the off-season. The outputs are being taken forward in a large-scale carbon-capture project, **Seaweed Carbon Solutions**[154].

Still needing investigation is the concept that the farming of seaweeds should mirror their life-style, which includes aspects such as whether and for how long they are intertidal or submerged, do they undergo wet-dry cycles or what their tidal depth variance is, how these interact with their physiology and productivity and, if they are significant contributors to biomass and components, how to translate this into farm design features. The cultivation system may perhaps be fixed in a situation mimicking natural growth, or may be flexible and dynamic so it follows the species, seasons and positions. There is also the question of how to help seaweeds survive and thrive even if sea temperatures increase, especially if the translocation and introduction of hardier seaweed species isn't possible. Here, gene editing using CRISPR techniques may be a way forward, one that CNRS Roscoff is working on for kelp and temperature-tolerance.

On-land cultivation is an attractive concept but it does not avoid some of the problems of costs of energy and issues with land-use and water-use. It also removes the broader ecological services aspect of seaweed farming although it may be contributing to bioremediation of other activities. has been successfully achieved by companies such as **Acadian Seaplants** of Canada, who produce 1,000 tonnes a year of Irish moss, *Chondrus crispus*, in bubble-aerated raceway tanks, starting from individual pieces of seaweed in the breeding lab, propagated vegetatively to produce a uniform product for the Japanese edible seaweed market[155]. They use wild *Ascophyllum nodosum* for other products for plant, animal and human health, harvested by hand or simple mechanical methods that prune seaweed fronds to 5 cm-20 cm to secure re-growth[156] and are currently developing a more-advanced mechanical harvester. The techniques and re-growth rates may be relevant for re-assessing amounts and frequency of wild kelp harvesting in north-west Europe.

1.6.1.3 IMTA and RAS, multi-use and circularity

IMTA, Integrated Multitrophic Aquaculture, is conventionally the co-cultivation of seaweeds and shellfish, or the farming of seaweeds in proximity to fish-farms, in a way that makes use of excess nutrients from shellfish and fish farming for seaweed growth or environmental bioremediation. The concept is now very well-established but there are newer aspects that are encouraging and represent innovation or improvement:

[152] https://www.macrofuels.eu/

[153] https://taredyrkingsfartoy2020.no/konseptet

[154] https://www.sintef.no/en/projects/2021/seaweed-carbon-solutions-jip/

[155] https://www.acadianseaplants.com/land-based-seaweed-cultivation/

[156] https://www.acadianseaplants.com/sustainable-seaweed-harvesting/

- **IMPAQT** (an EU project 2018-2021)[157] developed an intelligent management platform with novel sensors and data sources, and smart systems required for long term autonomous monitoring in the field, an IMTA ecosystems model for planning decisions by both farmers and regulators, and an integrated management system for on-farm operational decisions for animal welfare, production optimisation, environmental protection and food quality assessment;

- The EU project **IntegraSea**[158] (2019-2021) studied the potential for off-shore seaweeds to suppress toxic microalgae by nutrient takeout and thus protect shellfish farms, using high value native seaweeds and potentially producing seaweed extracts for 'natural' products from the harvests;

- in the **Long Island Seaweed Bioextraction** program[159], bench-top work confirmed that seaweeds like *Gracilaria* and kelp could suppress and damage harmful algal blooms like *Alexandrium*, resulting in saxitoxin content of exposed mussels that was less than FDA's closure level; *Pseudo-nitzschia* and domoic acid impacts were also suppressed or reduced by *Saccharina*; in another project, IMTA was set up with oysters and kelp, in water depths sometimes of less than 2m, using a specially-developed horizontal staked-line approach to seaweed farming. The advantage was that each line could be seeded by hand, walking through the water. 4 successful seasons were achieved without biofouling, and lines could be spaced 1.6-2.6 m apart, rather than 6 m as for conventional longlines. Yields were very satisfactory, equating to over 80 tonnes per hectare wet weight. In other work, sisal and manila hemp were successfully used instead of propylene for seaweed lines.

With interest in exploiting low-footprint land-based installations for seaweeds and microalgae, integration with sources of recoverable nutrients is a circularity goal. Recycling Aquaculture Systems (RASs) are a feasible way of doing this. In a conventional salmon or trout RAS, fish excreta accumulate as nitrate and nitrite that need scrubbing from the system. Using algae or marine microbes, this becomes an input for biomass production. Seaweeds can be used, mainly green or red, with the advantages of exclusion of grazers that can damage at-sea crops, control of environmental conditions and water quality and exclusion of microplastics. Using microalgae is also attractive. The **MARTINIS** project (2018-2024)[160] at University of Gothenburg Sweden, in collaboration with University of Hiroshima Japan, uses a novel Japanese marine bacterium, most likely a *Scalendua* species. It is a so-called anammox organism, capable of <u>an</u>aerobic <u>amm</u>onium <u>ox</u>idation, a type discovered only in 1999. These microbes completely metabolise dissolved nitrogen compounds into nitrogen gas and reduce the cost of integrated processes by as much as 60% as well as reducing the quantities of residual sludge. The bioreactor attached to the finfish RAS will also include novel membrane technologies to remove other micro-pollutants.

Multi-Use projects are generally restricted to co-location of seaweed farming (possibly with mussels) on wind farms, Wind+Weed or potentially with wave-power sites. Although technically the co-location is possible, in practice, wind-farm management is reluctant to include seaweed farming on-site, because of the risks introduced by the additional infrastructure, interference between the two operations and the lines, cables, anchors and boats involved, and potential for insurance difficulties.

- Explored initially for the North Sea in projects such as MUSES, one outcome has been **North Sea Farmers' Ocean Farm** initiative off the coast of the Netherlands[161]. Starting with a 40-hectare plot in 2022, the next phase will be to sequentially add on three more 40 Ha plots

[157] https://impaqtproject.eu/about-impaqt/

[158] https://cordis.europa.eu/article/id/430375-the-benefits-of-seaweed-cultivation

[159] Search for Long Island Sound Nutrient Bioextraction symposium on YouTube

[160] https://www.gu.se/en/research/martinis-mariculture-technical-innovations-in-sweden

[161] https://www.northseafarmers.org/projects/north-sea-farm-1

during 2024-2025 in order to validate design, management, monitoring and other operational aspects, ending with commercial-scale farms of 160 ha, aiming to produce 1,000 tonnes of seaweed a year. This is a collaboration between North Sea Farmers, Van Oord, The Seaweed Company and Algaia;

- The EU project **UNITED** (2020-2023)[162], in which three of the 5 planned pilot-scale at-sea multi-use farms will integrate seaweed into other activities, blue mussels and off-shore energy in Germany, floating solar energy in the Netherlands and off-shore wind, flat oyster farming and wild bed restoration in Belgium, all in the North Sea, up to 80 km off-shore.

There is considerable progress in **Circularity**, the use of outputs from one or more processes as inputs to another. In the context of alga systems, inputs are fluid: nutrient-rich liquids from industrial activities such as food processing, brewing and alcohol production, even marine hydrocolloid production, or from anaerobic digestion of residual solids; gaseous: mainly CO_2 itself or flue gases; and waste heat. The main factor reducing cost of logistics is co-location, which can be realistically-achieved on-land for microalgae and seaweeds. Even at sea, however, if accurate mapping and monitoring of nutrient flow and accumulation can be put in place, the bioremediative effects of seaweed could be harnessed in farm modules deliberately used to offset agricultural and anthropogenic eutrophication, possibly even as floating modules, movable according to concentration of nitrogen and phosphate run-off or sewage pollution, provided licence and MSP restrictions can be overcome.

Examples of interesting projects include:

- an **Algae-UK BIV** project (Business Interaction Vouchers, up to £10,000 funding/project), for a collaboration between Swansea University and CGG Services (UK) Ltd, to explore the technical and economic feasibility of the recycling of warmed cooling water from a Data Processing Centre (DPC) through microalgal systems and back to the DPC's heat exchanger when cool, with flue gas emissions as a CO_2 source[163];
- The UK BEIS's **Biomass Feedstocks Innovation Programme**[164] has funded several relevant projects:
    - Gold to Green to Gold (3Gs), led by Phycofoods Ltd, used the whisky by-products CO_2 and anaerobic digestion digestate as inputs into a 5000 litre Advanced Photobioreactor (Pandora™ APBR, Xanthella Ltd). The APBR, developed from a smaller rectangular plastic APBR with internal flat-panel light guides, is a stainless-steel cylindrical vessel with internal and external light sources of appropriate wavelengths and managed gas injection, which also mixes the microalgal suspension in the liquid. In the APBR, 100% of the light reaches the microalgae, excess heat from the LEDs can be recovered and the design means that sterilisation and re-use are simplified. The APBR is expected to allow a reduction of 90% in materials and space requirement compared with a conventional tubular PBR of the same volume. The microalgal biomass will be used as biostimulant to improve barley production or as feed for aquaculture;
    - The MISTY (Microalgae Biomass Sustainability) project, led by Green Fuels Research Ltd, using brewing wastewater as input to a mixotrophic co-culture of *Tetradesmus obliquus* microalgae with bacteria; the consortium had over 4-fold growth performance at lab-scale and 8.6-fold at scale-up, compared with the microalgae alone, explained by the microalgae producing O_2 for the bacteria to use and the bacteria supplying CO_2, fixed nitrogen, vitamin B, phytohormones, and siderophores (high-affinity iron-

[162] https://www.h2020united.eu/

[163] https://www.algae-uk.org.uk/projects/biv-round-2-feasibility-study-of-the-re-use-of-exhaust-heat-from-a-data-centre-to-grow-microalgae/

[164] See links in https://www.gov.uk/government/publications/apply-for-the-biomass-feedstocks-innovation-programme

chelating compounds) to microalgae. The culture system also allowed production of microalgae biomass in the wintertime;

- Integrated microalgae biomass production via carbon dioxide sequestration, led by SEaB Power Ltd, in which there was on-farm integration of existing commercial-scale modular anaerobic digesters with production of microalgal biomass of *Spirulina*, *Chlorella*, *Nannochloropsis* & *Scenedesmus* in PBRs powered by energy output from the digesters; the anaerobic digesters are already sold for processing food or feed wastes and manure and are automated and remotely-monitored. 500-3000 kg/day of cattle waste feed and faeces were processed on-site, producing sterile liquid fertiliser and residual biomass which was dewatered using belt-pressing and membrane filtration, with organic flocculants as necessary, and returned to the cattle as feed supplement;

- growing *Saccharina latissima, Ulva fenestrata, U intestinalis* and *Chaetomorpha linum* in outflows from herring, shrimp and oat-milk processing and in salmon RAS outflows, for nutrient capture, bioremediation and generation of edible biomass; in lab-scale work, 64% higher growth and almost four-fold increase in dry-weight protein content (25% vs 6.5%) was achieved[165]. The work, at the **University of Gothenburg Sweden**, has been scaled-up into 500 litre tanks and post-harvest cultivation of Ulva has also been tested for 14 days; using herring processing waters, the same outcomes of increased protein content have been achieved, with heavy metal levels well below EU acceptance thresholds and no change in sensory qualities[166,167].

The nature of 'waste' liquid or digestate components suggests that mixotrophic cultivation will be more efficient than photoautotrophic open-pond or PBR systems and this is supported by findings that mixotrophic algae can remove emerging pollutants as well as established inorganic and organic pollutants; consortia of microalgae and other microbes are also efficient at removing pharmaceutical residues. However, microalgal growth is inhibited unless digestate is diluted, filtered and pre-aerated to avoid concentrated components and turbidity. Contaminants that reduce the utility of the microalgal outputs include household, agricultural and pharmaceutical chemicals and antimicrobials, and when animal and human wastes are used, antibiotics and antimicrobial resistance genes. A wide range of pathogens (*E coli*, *Enterococcus*, *Bacillus cereus*, *Clostridium perfringens*, *Salmonella enteritica*, *Listeria*, *Cryptosporidium*, *Giardia* and intestinal helminths) has also been detected in digestate. Concerns with respect to heavy metals and other elements include the presence of excess copper, nickel, zinc, lead, aluminium and cadmium. Promisingly, many studies report bioremediation capacity of microalgae for removal of heavy metals and pollutants via cell-wall adsorption, and elimination of eutrophicating levels of macronutrients by metabolism, up to 99% for nitrogen, phosphorus and total organic carbon.

1.6.2 Processing technologies

1.6.2.1 Biorefineries

Thierry Chopin, a long-term practitioner in seaweed farming for industrial uses, is a proponent of integrated sequential biorefinery (ISBR) processing rather than simultaneous extraction. The concept is of a single biomass (which could be mixed-source, tailored to the desired outputs) undergoing several

[165] Stedt K, Trigo JP *et al*. (2022) Cultivation of seaweeds in food production process waters: Evaluation of growth and crude protein content *Algal Res* 63: 102647 doi: 10.1016/j.algal.2022.102647

[166] Stedt K, Gustavsson O et al. (2022) Cultivation of *Ulva fenestrata* using herring production process waters increases biomass yield and protein content *Front Mar Sci* 13 September 2022 doi: 10.3389/fmars.2022.988523

[167] Stedt K, Steinhagen S *et al*. (2022) Post-harvest cultivation with seafood process waters improves protein levels of *Ulva fenestrata* while retaining important food sensory attributes *Front Mar Sci* 26 September 2022 doi: 10.3389/fmars.2022.991359

processes in turn, yielding a range of bio-based, high-value compounds as well as lower-value commodity energy compounds[168]. This concept of sequential processing also lends itself to the concept of modular processing, with different stages designed as 'drop-in' or 'plug-in-plug-out' components, a concept we could describe as "Nimble Processing[169]". Smaller, more flexible processing plants would reduce the high cost of monolithic large-volume systems.

The conventional strategy to operate a microalgae operation is either to avoid massive drying - energy costs of all water-removal stages are excessively high unless solar drying or green energy is available - or to produce high-value products to offset the high processing costs. For fractionation of components, cells need to be physically disrupted, most often by high-pressure homogenisation, agitating with ceramic or glass beads, autoclaving, microwaving, freezing and osmotic shock, trending towards pulsed electric field and ultrasonic disruption. Chemical extraction and conversion is by use of ionic liquids, organic solvents for biofuel lipids, more sustainably and contamination-free by supercritical fluid extraction (SFE) or use of Deep Eutectic Solvents (DESs), mechanical removal or ultrasound procedures, and supercritical CO_2 for high-value nutraceuticals and biochemicals/bioactives[170].

Microwave-assisted extraction (MAE) appears a very attractive processing tool for microalgal and for seaweed biorefineries due to its advantage of easy operation, high energy transfer efficiency, rapid heating and relatively low cost. MAE has been shown to be highly effective for pigment and lipid extraction from microalgae, e.g. 5 minutes' MAE of the European marine diatom *Cylindrotheca closterium* enabled maximal extraction of fucoxanthin equivalent to 60 minutes of conventional solvent extraction method. With the addition of ionic liquids, MAE has been applied to extract lipids from wet microalgal biomass where extraction rates were increased by an order of magnitude in most cases. The use of ***Deep Eutectic Solvents*** also appears very interesting. They have already been used experimentally for extraction of omega-3 fatty acids from *Nannochloropsis*[171]; production of chitin, chitosan and astaxanthin from crustacean shells, a variety of components from fish and fish wastes, and hydrocolloids, fucoidans and even graphene nanosheets from seaweeds[172]; and phlorotannins from Fucus and Ascophyllum, when the DESs were based on choline chloride, betaine, glucose and lactic acid in various combinations[173]. Scale-up of DES use for a variety of commercial outputs of seaweed is being carried out in the SeaSolv project[174].

1.6.2.2 Microalgae

The trend to applying innovative technologies at research and pilot-scale level may sometimes reveal really forward-looking ones, such as those in the EU-funded projects ValueMag and AlgCoustics below, which deserve wider assessment. Interesting examples include:

- **ABACUS** (2017-2020)[175], set up to develop an algal biorefinery for high-end applications, including algal terpenes for fragrances and long-chain terpenoids (carotenoids) for nutraceuticals and cosmetic actives. ABACUS partners provided strains from their own culture collections for optimisation. Other achievements were online monitoring and automated control

[168] https://thefishsite.com/articles/seaweed-aquaculture-panacea-or-hype-imta N Holmyard 6.4.22

[169] ©L P M Lloyd-Evans 2022

[170] Pierobon SC, Cheng X et al. (2018) Emerging microalgae technology: a review Sustain Energy Fuels 2: 13 doi: 10.1039/c7se00236j

[171] Moreno Martínez P, Ortiz-Martínez VM *et al.* (2022) Deep eutectic solvents for the extraction of fatty acids from microalgae biomass: Recovery of omega-3 eicosapentaenoic acid *Sep Purif Technol* 300: 121842 doi: 10.1016/j.seppur.2022.121842

[172] Reviewed in McReynolds C, Adrien A *et al.* (2022) Green in the deep blue: deep eutectic solvents as versatile systems for the processing of marine biomass, Green Chem Lett Rev 15(2): 383-40 doi: 10.1080/17518253.2022.2065890

[173] Obluchinskaya E, Daurtseva A *et al.* (2019) Natural Deep Eutectic Solvents as alternatives for extracting phlorotannins from brown algae *Pharm Chem J* 53(3) doi: 10.1007/s11094-019-01987-0

[174] https://www.wur.nl/en/newsarticle/seasolv-enables-waste-free-multiproduct-biorefinery-of-seaweed.htm

[175] https://www.abacus-bbi.eu/

of photobioreactors and development of specific sensors for terpenes and for the parameters relevant to terpene production (light, pO_2, pCO_2, nutrients);

- the **AlgCoustics** project in the EU's Marie Skłodowska-Curie programme, in which a sequence of ultrasound followed by combinations of acoustic waves at different frequencies is being used to fragment cells and then drive apart the different cell components by field forces[176]. Currently at microscale ('lab-on-a-chip'), the work aims for a 'Single-step disentanglement and fractionation' of microalgal high-value products through acoustophoresis;
- another EU Marie Skłodowska-Curie Action, **Algwas-Bior** (2021-2024), aimed at valorising the waste stream from the existing *Gelidium*-processing food hydrocolloids industry, partly for high-value extractables and partly for bioenergy. Part of the project is to put elements of Aquaculture 4.0 in place, i.e. generation and capture of high-quality process performance data, automated data acquisition, automated process control systems and new advanced analytical methods;
- **Brevel**, in an SME Industrial Leadership project (2020-2022)[177], developing a pilot-scale 400 tonnes/year indoor PBR with internal light supplementation and automated process management, including full automation with precise control of temperature, pH, oxygen levels, light spectrum and an advanced fermentation process with a high concentration of internal illumination. The overall improvements in efficiency expected were x10 for growth rate, x200 in land productivity, 90% cost reduction, 100% consistency and 10% the employee headcount;
- **CYCLALG** (2016-2019)[178], an Interreg V-A project which integrated thermo-mechanic fractionation of agrifood liquid waste outputs, as nutrient inputs to microalgal PBR production for biofuel oils, with enzymatic hydrolysis of the defatted algal biomass and wastewaters for aminoacids and sugars;
- **SABANA** (2016-2021)[179], which used marine water and nutrients from wastewaters (sewage, centrate and pig manure) to produce biostimulants, biopesticides, feed additives, biofertilisers and aquafeed, using microalgae-bacteria consortia and microalgal co-cultures to control grazing species, an efficient thin-layer cascade and raceway in a demonstrator of 5000 m^2 and development of wet-biomass harvesting and processes for mild/energy efficient extraction of bioproducts; a scale-up demo raceway is being built, of 10,000 m^2, fed by urban wastewater;
- the EU-funded Bio-Based Industries Joint Undertaking project **ValueMag** (2017-2020), which used superparamagnetic nanoparticles to magnetise microalgae and allow faster, more efficient and environmentally-friendly separation of biomass from cultivation media, fragmentation of cells and separation of product streams[180]. Though the pilot-scale magnetic PBR was not validated, binding molecules (ligands) added onto the magnetic nanoparticles trapped astaxanthin and allowed rapid high-purity extraction (95% pure astaxanthin, compared to 60%-70%, within 15 minutes, compared with hours of membrane separation) and a ligand-based potential human medical application was discovered, targeting tissues such as cancers.

1.6.2.3 Seaweeds

The harsh nature of extraction methods for seaweed hydrocolloid production, globally the most important current commercial use, limit or even destroy further use for fractionation, food or feed.

[176] https://www.wur.nl/en/project/Single-step-disentanglement-and-fractionation-of-microalgal-high-value-products-through-acoustophoresis.htm

[177] https://brevel.co.il/

[178] http://www.cyclalg.com/en/acciones/actividades/

[179] http://www2.ual.es/sabana/

[180] https://www.valuemag.eu/consortium/

Moving away from dried biomass to being able to use wet biomass avoids a major part of energy, capital and processing costs and allows larger amounts to be processed closer to the point of production or harvesting. A challenge is to avoid degradation or spoilage of biomass during processing, especially transportation and drying. Several efforts are underway to extend time before wet biomass spoils: **Green Ocean Farming** is one company attempting this[181]. The difficulties of cost and logistics of transportation from point of production to processing remain to be attacked for seaweeds; for microalgae in open ponds or bioreactors, this is less of a challenge. There are still challenges in valorising wet biomass when fractionated components are the target, but use of green energy or integration with spare power and on-site batteries in Wind+Weed co-locations will reduce costs[182,183]. With advanced digital management, as envisaged in Aquaculture 4.0, at-sea processing and biorefining might be possible.

It is conceptually easier to imagine the mass processing of wet seaweed biomass for commodity uses such as fertiliser, soil improver, ensiled animal feed and biofuels production, so one challenge that should be overcome for future expansion is how to produce higher-value product streams through seaweed and microalgae biorefineries that deal with wet or only moderately dewatered material.

For biofuels, the most promising technologies for extracting energy value from wet seaweed biomass (up to 85% moisture) that totally avoid the costs of de-watering and drying are combinations of high temperatures and pressures[184]:

- hydrothermal liquefaction (HTL) - at 200-380^{0}C and 5-28 MPa pressure HTL creates high-value crude bio-oil and other fractions in minutes with moderate use of exogenous energy;
- hydrothermal carbonisation (HTC) - at 180-250^{0}C and 2-10 MPa pressure HTC produces biochars and fractionatable liquids, and chemical precursors such as levulinic acid have also been generated by adding microwave-assistance[185];
- supercritical water gasification (SCWG) – this requires 400-700^{0}C and >22 MPa pressure, so is more energy-intensive, to completely crack biomass to syngas (a mix of H_2, CO_2 and CH_4) with residual solids and liquids. with a small quantity of solid and liquid products.

For these, the need for catalysts and high-resistance materials adds costs and all require process-tuning for optimum yield according to the biomass character, suggesting the need for pilot-scale units within industrial-size plants to fix the best process conditions, and smart monitoring tools for rapid response during processing. If drying is economically-feasible, high temperature anoxic pyrolysis can be used to generate bio-oil and biochar. These processes would also be valid for wet-biomass microalgae that is not intended for high-value fractionation.

As for microalgae, the current trend for extraction of useful components or higher-value bioactives is to simpler processes with fewer or no harsh or toxic reagents or steps, that are shorter to end-point and less energy-intense:

- a project on green processing supported by UK BEIS via **Algae-UK**, using a fast water-based thermochemical process to replace a longer one based on formaldehyde, with seawater and CO_2 instead of commercial sodium carbonate for the extraction of alginate, degrading alginate

[181] https://www.greenoceanfarming.com/buy-a-seaweed-farm.php

[182] Moshood TD, Nawanir G et al. (2022) Sustainable Business Model Innovation and perspective of using microalgae to produce biofuel: a systematic literature review J Sustain Sci Manag 17(3): 304-325 doi: 10.46754/jssm.2022.03.022

[183] Dębowski M, Zieliński M et al. (2020) Microalgae Cultivation Technologies as an Opportunity for Bioenergetic System Development—Advantages and Limitations Sustainability 12: 9980 doi: 10.3390/su12239980

[184] S. C. Pierobon SC, Cheng X *et al.* (2018) Emerging microalgae technology: a review *Sustain Energy Fuels* 2: 13 doi: 10.1039/c7se00236j

[185] Deng C, Lin R *et al.* (2022) Co-production of hydrochar, levulinic acid and value-added chemicals by microwave-assisted hydrothermal carbonisation of seaweed *Chem Eng J* 441: 135915 doi: 10.1016/j.cej.2022.135915

in the early stage to reduce the viscosity of the alginate mixture and improve downstream processing efficiency and costs for applications such as wound dressings[186]. The project also expects to develop a pioneering CO_2 sequestration process;

- Brazilian work on extraction of *Gracilaria birdiae* carbohydrates using sulphuric acid[187]: this is a tropical red seaweed with a high carbohydrate content but understudied as a potential renewable resource compared with *G. dura*, *G. verrucosa* or *Kappaphycus alvarezii*. Acid hydrolysis of biomass produces glucose, galactose, cellobiose, 5-hydroxymethylfurfural, levulinic acid and formic acid. Each target output required different hydrolysis conditions (temperature, pH and time). These platform chemicals can then enter a large number of value-chains including pharmaceutical products, solvents, resins, polymers, fungicides, pigments, fuels, flavouring agents, solvents, plasticisers, anti-freeze agents and biofuels/oxygenated fuel additives, agricultural, textile, pharmaceutical, and rubber industries or act as a precursor to specialty chemicals;
- a process for fucoidans developed by **Marinova**, an Australian seaweed bioactives company, using air-dried wakame *Undaria pinnatifida* and bladderwrack *Fucus vesiculosus*. Rather than using conventional solvents to precipitate fucoidan there is an aqueous extraction followed by proprietary filtration, de-watering and drying to a powder[188]. Marinova is investigating the extract's clinical uses in helping boost the immune response to seasonal influenza vaccinations and increasing the anti-pathogenic activity of granulocytes and macrophages in healthy people;
- the Indian company **Sea6 Energy** started its seaweed-to-biofuel value-chain with a collaboration with Novozymes to use high-performance fermentation enzymes for production of fuel ethanol, fine chemicals, and protein from seaweed carbohydrates, announced in 2012. In addition to use of enzyme-fermentation, Sea6 Energy has also developed minimal-freshwater and shelf-life-preservation technologies (up to 60 days after harvest)[189];
- in the **SeaSolv** project, Wageningen University & Research (WUR) is aiming to establish Deep Eutectic Solvents (DESs) as the processing tools of choice for extracting phycocolloids from seaweed[190]. WUR is working with HortiMare, KelpBlue, Algaia and the University of Aveira, funded by NOW, the Netherlands Organisation for Scientific Research. DESs are typically a mix of an ammonium ion donor, such as choline chloride, with a hydrogen bond donor, which can be derived from organic starters such as simple sugars, with the attractions of low cost, potential biodegradability and low or no toxicity.

Bioreactor and biorefinery technologies are a clear target for improvement. Creating a suitable system within which to extract and separate these materials is the subject of the many biorefinery projects supported by the EU, some of which aim for circularity by using input nutrients from process outflows:

- **ALEHOOP** (2020-2024)[191] is squarely aimed at import substitution of soya protein by locally-produced feed proteins, of both macroalgal and leguminous origins, developing pilot-scale biorefineries;

[186] https://www.algae-uk.org.uk/projects/the-development-of-a-greener-extraction-process-for-the-production-of-alginate-for-medical-application/

[187] Albuquerque JCS, Aráujo MLH *et al.* (2021) Acid hydrolysis conditions for the production of fine chemicals from *Gracilaria birdiae* alga biomass *Algal Res* 53: 102139 doi: 10.1016/j.algal.2020.102139

[188] https://marinova.com.au/extraction-technology/

[189] www.sea6energy.com

[190] https://www.wur.nl/en/newsarticle/seasolv-enables-waste-free-multiproduct-biorefinery-of-seaweed.htm

[191] https://alehoop.eu/

- **CIRCALGAE** (2022-2026)[192], developing integrated biorefineries at 10^2s kg scale to use waste streams from hydrocolloid and carotenoid production, processing using water-based technologies, for texturisers, high-value bioactives and high-nutrients for the value-chains of texturised vegan foods, health-promoting food ingredients, protein-rich feed, cosmetic formulations and highly bioactive ingredients for topical use. The project will expand sources of fucoidans and fucose derivatives beyond *Laminaria hyperborea*;
- **GENIALG** (2017-2021)[193], increasing production and sustainable use of *Saccharina latissima* and *Ulva* off-shore and on-land respectively. The project developed genome-wide analysis and a customised phenotyping platform for seaweed strain selection and improvement, created novel marine enzymes and enzyme cocktails for seaweed fractionation and produced a seaweed biorefinery booklet to disseminate the concept[194]. The plans are to scale-up to 1000 tonnes a year of off-shore *Saccharina* and to design and demonstrate mechanised, modular onshore cultivation units for *Ulva*, which can be reproduced according to availability of space – modularity is a key feature of future developments;
- **MACRO CASCADE** (2016-2021)[195], a wide-focus project where the eventual residue was to be used for fertilisers and bio-energy;
- **Macrofuels** (2016-2019)[196] processed seaweeds into advanced biofuel, including ethanol, butanol, furanics and biogas, using novel fermenting organisms with high capacity (90%) to convert algal sugars into bioethanol and biobutanol, and biogas producers able to convert 90% of available carbon. Another improvement was the pre-treatment and storage of seaweed to yield fermentable and convertible sugars at economically relevant concentrations (10-30%);

Many projects recently approved and underway in the EU and elsewhere are aiming to address the critical issues facing economic upscaling of seaweed- and microalgal-base economies, from biobanks and genomic tools through tackling the costs of energy and processing and developing remote-monitoring, big-data decision-making and automated responses to building cheaper, effective large-scale cultivation and harvesting systems. The on-going challenges of building efficient biorefineries with cost-effective fractionation techniques is one that has been invested in by the EU for two decades or more.

The Safe Seaweed Coalition[197] has put €700,000 into 16 projects in their first call in November 2021, and funded 8 more in their Spring 2022 call. Some may well yield viable next steps in answering bottlenecks and gaps, within and outside Europe:

- a centralised European biobank for seaweeds at the Alfred Wegener Institute (already identified as a short-term action by the EU Algae Initiative);
- a framework for Baltic seaweed biosafety to aid monitoring and licensing;
- an algal biorefinery using natural marine bacteria as processing agents;
- the use of environmental DNA monitoring to study and follow kelp forest impacts;
- collection and selection of superior indigenous seaweeds in Madagascar;
- biobanks of Micronesian seaweeds at Banco Español de Algas, Islas Canarias;

[192] https://cordis.europa.eu/project/id/101060607
[193] https://genialgproject.eu/2021/08/19/genialg-project-results-help-to-boost-the-european-seaweed-sector/
[194] https://genialgproject.eu/biorefinery-manual/
[195] https://www.macrocascade.eu/
[196] https://www.macrofuels.eu/
[197] https://www.safeseaweedcoalition.org/

- hatchery techniques for Australian kelp farming; and
- testing for heavy metals and nutritional variances at different sites in the USA.

1.6.2.4 Aquaculture 4.0 and automation

The concept of Aquaculture 4.0 is based on "Industry 4.0", the fourth industrial revolution, referring to the stage of developments that are managed by technologies such as the Internet of Things, remote monitoring, Big Data analysis and robotic responses, which provide the capacity for real-time detection and action. It builds on previous stages with increasing use of technology, monitoring and analysis to improve management of aquaculture processes and sustainability, quality, yields and impacts of operations. Version 1.0, which is unsophisticated labour-intensive production with low density, such as unimproved open pond cultivation or low-scale and simple seaweed IMTA ropes. An example of intermediate 3.0 technology might be the low-cost sensor system for monitoring growing environments developed by a social enterprise based in Wales, **PEBL** (Plants Beyond Land), with support from UK's Industrial Strategy Challenge Fund[198]. Their "SeaLens" consists of three modules that can be mounted standalone or linked for ease-of-use. SeaLens and its data are intended to inform planning and decision-making at pre-investment stages as well as field use. PEBL's aim is 'to empower coastal communities by developing methods of cultivating, monitoring and protecting native-seaweed species'. They use photovoltaic energy to power their on-land hatchery housed in shipping containers and grow dulse (*Palmaria palmata*), laver (*Porphyra umbilicaris*), and *Saccharina latissim*a.

Aquaculture 4.0 has the aim of reducing operating costs and intensivity of labour, improving management actions to minimise reaction times and allowing large-scale or remote operations. It is projected to allow the entire aquaculture sector to grow by 15-20% by 2030[199]. Monitoring and data capture still have a very high cost, especially in seaweed farming, because so much of it has to be manual, even a decision on when to harvest, which could otherwise be made by an in-computer 'digital twin' that integrates growth and density data and oceanographic and weather monitoring in real-time. Analysis of genetic diversity and monitoring of growth density would be first useful targets for low-cost high-performance systems, with disease detection close behind.

To-date, most applications of Aquaculture 4.0 principles have been in fish farming, where examples include intelligent auto-feeders for minimising feed wastage, smart aerators for optimised oxygen supply and saving electricity, connected sensors for water conditions such as dissolved oxygen and temperature, and water current and weather event sensors. The systems use solar power or photovoltaics or, more recently, wave power as energy sources for signal detection and transmission[200]. The first fish farm entirely supported by Aquaculture 4.0 systems was opened in 2021 in Singapore[201], producing barramundi. The smart technologies being used in what the company **Singapore Aquaculture Technologies**[202] calls 'plug-and-play' farms were developed by Siemens AG and integrate Artificial Intelligence and video analytics. The system allows remote management of fish nutrition, early warning of disease, testing and selection of feeds, monitoring of behaviour and determination and forecast of numbers and weights of fish per tank. Further developments may include on-site analysis of water microbiome.

The US company **Running Tide** is using advanced monitoring, measurement and diagnostics alongside seaweed enhancement and shellfish replacement projects as part of ocean regenerative activities, using floating farms[203].

[198] https://www.plantsbeyondland.com

[199] https://ifishienci.eu/2021/10/20/survey-the-future-of-aquaculture-the-impact-of-industry-4-0-technologies-worldwide/

[200] See, for example, https://www.innovationnewsnetwork.com/aquaculture-4-0/596/

[201] https://sat.com.sg/today-online/ai-keeps-an-eye-on-barramundi-at-smart-floating-fish-farm-off-pasir-ris-coast/

[202] https://sat.com.sg/

[203] https://www.runningtide.com/restoration

Within Horizon 2020, the EC established a programme "**Sustainable European aquaculture 4.0: nutrition and breeding"**, including in the term fish, invertebrates and algae[204]. Elements included zero waste and by-products valorisation following circularity principles, exploration of the potential of the microbiome on health and productivity of farmed species, upscaling of the production processes to pre-commercial product, consideration of the use of Internet of Things (IoT) and Artificial Intelligence (AI) and participation of deep-tech start-ups. The programme is intended to cover all maritime areas of Europe and to contribute to a wide range of policies and strategies. In addition to common themes such as demonstration that investment in sustainable aquaculture research and innovation leads to the creation of new value chains and markets, algae are specifically mentioned in the context of genetic diversity and implied in topics of creation of improved sustainable aquaculture systems and productive and resilient aquaculture practices that maintain healthy aquatic ecosystems. As of today, 4 projects are being funded under the programme: NewTechAqua, FutureEUAqua, AquaImpact and iFishIENCi[205].

Many aspects of microalgal production in PBRs and fermenters are already digitised, since the containment lends itself to automation, remote monitoring and algorithm-driven responses. For extensive production, the potential for robustly and safely co-locating seaweed farms with other utilities such as wind-farms and managing huge-scale carbon-sink set-ups should be simplified. Examples of Aquaculture 4.0 applications for algae include feeder robots that measure water quality, biomass and make precise decisions, mathematical modelling of seaweed crops to optimise yields, drones for inspection of ponds or farms, autonomous vehicles recording sub-surface conditions and appearance and growth of seaweeds in ocean farms, real time use of the internet cloud, and control of production processes using mobile phones and artificial intelligence algorithms[206] .

Another example of integrated Aquaculture 4.0 is the EU-funded Horizon 2020 project **iFishIENCi** "Intelligent Fish feeding through Integration of Enabling technologies and Circular principles" (2018-2023)[207]**.** The project has several elements of advanced digital information technology, highly-digitised monitoring, analysis and responses, fish-tagging technology for video assessment of fish behaviour and a digital twin of fish digestion efficiency. Sensors and feeders will be incorporated into an 'Internet of Things' environment. This includes the development of data aggregation and analytical processes that interact with sensors, artificial intelligence learning and cloud data storage, sensors, automated feeders, artificial intelligence and novel feed formulations, finally testing in commercial environments.

For those companies and organisations with access to **North Sea Farmers' Offshore Test Site**[208], many aspects of remote monitoring that could form part of the 4.0 platform are already available. They include access to the Dutch company Svašek's weather forecast model, real-time data measurement of offshore turbidity, conductivity and temperature and content of chlorophyll-A, Nortek's Doppler-effect vertical flow profiler and a DAS (Distributed Antenna System) module that accesses a LoraWan-based network[209], with the possibility of adding an Automatic Identification System (AIS), GPS-sensors and a Compact Weather Station.

[204] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/dt-bg-04-2018-2019

[205] Please see: https://cordis.europa.eu/search?q=contenttype%3D%27project%27%20AND%20programme%2Fcode%3D%27DT-BG-04-2018-2019%27&p=1&num=10&srt=/project/contentUpdateDate:decreasing

[206] Further background in Morales IR (2022) https://aquaculturemag.com/2022/02/24/aquaculture-4-0-technological-innovation-as-a-competitive-advantage/

[207] https://ifishienci.eu/

[208] https://www.northseafarmers.org/offshore-test-site

[209] https://lora-alliance.org/about-lorawan/

1.7 Market context

Given the breadth of possibilities for products from microalgae and macroalgae, from the currently well-known hydrocolloids and carotenoids to as-yet unvalued ecoservices, attempting to analyse target market sectors is not realistic.

1.7.1 Regulation and standards

From an industry's perspective, it is difficult to know whether regulations are a Challenge & Barrier or are facilitators of market access. Here, some opportunities of regulatory frameworks should be assessed. This includes the role of standards in regularising an industry and creating a relatively level playing field, as well as the importance of certification programmes that validate consumer acceptability and traceability, very important aspects of establishing a true circular economy.

In the EU Algae Initiative, the Commission notes that, as algal cultivation falls within the remit of aquaculture legislation, which is managed by the EU MSs, the only piece of legislation where direct action can be taken at Commission level to favour more algal initiatives would be to amend the Fertilising Products Regulation EU 2019/1009, which already has 5 component categories including algae and algal products[210].

Whatever progress might be made in technology or commercialisable products, when it comes to practical actions like establishing new farming or manufacturing sites, these face frameworks such as Social Licence to Operate, Permit and Licence Authorisation regimes and requirements to demonstrate no adverse environmental, ecological or biodiversity impacts. The EU Algae Initiative's proposed 'algal toolkit' will help to navigate these and other aspects of setting up algal businesses.

The EU Algae Initiative has usefully made a start on a compendium of EU legislation that needs to be considered before undertaking algal activities, from farming to products[211]. EABA has also published a comprehensive analysis of the Novel Foods Regulation, in general and as it applies to algae, together with information on markets for products and species of interest[212]. EABA notes that we should be aware that a NFR approval is specific to the product of the defined process and is not a general approval for the source species or its products – the example given at an EU4Algae workshop was Kemin's BetaVia Complete, beta-glucan from *Euglena*, which was misleading for other companies wanting to market products from *Euglena*.

The European Commission, recognising the need to accelerate expansion of algae in the EU, especially in the context of sustainability, instructed the European Committee for Standardisation in 2016 to develop standards to assist deployment of algae for biofuels[213]. CEN/CENELEC's Technical Committee TC/454 has been developing standards for algal products, see the Table below. The work of the Committee has now expanded from renewable energy requirements to include food and feed, chemicals, cosmetics and pharmaceuticals and so will assist establishing output in many of the value-chains.

[210] See SWD(2022) 361 final, pp 39, 79 and others

[211] See pp 74-83 of SWD92033) 361 final

[212] *Algae as sources for Novel Foods – EABA White Paper* EABA 27.11.2020 https://www.algae-novel-food.com/

[213] European Commission Implementing Decision M/547 C(2016) 1582 final 23.3.2016

Table 1.1: Standards developed by CEN TC/454 related to algae

EN/CEN no.	Title and subject matter
EN 17339:2020 [revision in 2022]	Algae and algae products – Terms and definitions
EN 17477:2021	Algae and algae products – Identification of the biomass of microalgae, macroalgae, cyanobacteria and Labyrinthulomycetes – Detection and identification with morphological and/or molecular methods
EN 17480:2021	Algae and algae products – Methods for the determination of the productivity of algae growth sites
EN 17605:2021	Algae and algae products – Methods of sampling and analysis: Sample treatment
CEN/TR 17559:2022	Algae and algae products – Food and feed applications: General overview of limits, procedures and analytical methods
CEN/TR 17611:2021	Algae and algae products – Specifications for cosmetic sector applications
CEN/TR 17612:2021	Algae and algae products – Specifications for pharmaceutical sector applications
CEN/TR 17739:2021	Algae and algae products – Specifications for chemicals and biofuels sector applications
prEN 17908	Algae and algae products – Methods of sampling and analysis – Determination of total lipid content using the Ryckebosch-Foubert method
(WI=00454007)]	Algae and algae-based products or intermediates – Methods of sampling and analysis – quantification of chlorophyll
(WI=00454013)	Algae and algae products — Sampling — Guidelines for the definition of sampling programs and sampling protocols
(WI=00454014)	Algae and algae products — Determination of the amino acid profile of micro- and macroalgae
(WI=00454016)	Algae and algae products —Determination of inorganic arsenic in algae and algae products by anion-exchange (HPLC-ICP-MS)
(WI=00454017)	Algae and algae products — Nitrogen content measurement and protein content calculation for micro- and microalgae
(WI=00454012)	Algae and algae products - Measurement for renewable algal raw material for energy and non-energy applications

Activities in advanced automation, robotic monitoring, harvesting and processing and computer-integrated manufacturing also need to consider the outputs of CEN/CENELEC TC 310, Advanced Manufacturing Technologies[214].

Licences are needed for sites for farming and for seaweed-farm vessels, including harvesters, limiting the volumes in the same way as fish catches, and specifying the purposes. In mussel-seaweed IMTA, seaweed is often harvested using mussel-harvesters, sometimes with winch adaptations or other small changes. Funding the building of specialised vessels, especially for the larger farms planned further out at sea, is a challenge, especially as harvesting is seasonal. The Dutch authorities have granted a permit to North Sea Farmers, for a 6 km^2 site 12 km off the Dutch coast, as an Offshore Test Site for pilot-scale operations projects[215]. This is a blanket permit, not requiring re-negotiation by every company or organisation wanting to carry out a project at the site.

Alginor also notes the situation in Norway with licensing for harvesting wild kelp: This is regulated jointly by the Directorate of Fisheries and four relevant counties, based on work by the Institute of Marine Research. The coastline is divided into c. 450 parcels one nautical mile high, numbered and lettered A–E, so that parcels with identical letters are open for harvest simultaneously for one year and each parcel is rested for 4 years. This approach provides for ample regrowth and sustainable harvests and, following inspection in year 5 by The Institute of Marine Research, the county councils approve an updated harvest list. It is the Directorate of Fisheries that licences harvesting with mechanised equipment and the amount and position of all catch must be reported. The current yearly limit of kelp

[214] https://standards.iteh.ai/catalog/tc/cen/bcf2a459-0feb-47a7-b978-5eb71e95627b/cen-tc-310

[215] https://www.northseafarmers.org/offshore-test-site

harvest of 170,000 tonnes (c. 0.3 % of the total biomass in Norway) is dwarfed by the c. 20 million tonnes of kelp forests grazed by sea urchins in Northern Norway and the c. 7.5 million tonnes lost to storms each year, as noted by Alginor. As the harvested kelp fields are fully regrown within 3–5 years, the regulated harvest in Norway ensures a sustainable utilisation of *L. hyperborea*, but many of those in the algae sector believe the limits are too restricted.

The need to simplify licensing has been noted; this will become more pressing if floating and mobile robotic seaweed farms are developed, for example to make best use of nutrient well-up off-shore, or land and estuary run-off or sewage outflows closer to shore.

Social Licence to Operate

Social Licences to Operate (SLOs) imply that the founders of new algae initiatives and activities have discussed their plans with and listened to local stakeholders, and more distant ones in their chosen value-chains if they have a position of influence, to explain their plans and deal openly with concerns, disharmony and opposition. Gaining an SLO is very much an exercise in Communication and Transparency. Science is not everything, in this exercise. SLOs are an important aspect of seaweed-farming and wild seaweed harvesting, perhaps less so for microalgal cultivation.

The ***Lloyd's Register*** Foundation, in its Manifesto[216], recognises there is a need for Social Licence acceptance and incorporation in Marine Spatial Planning of large-scale off-shore seaweed farming. Potentially, gaining a social licence to operate may shorten the time to get permits where the licensing process is otherwise slow, but companies also need to take into account spatial planning and the needs of other users.

Cargill's Red Seaweed Promise[4] (a phrase which the company has trade mark protected) answers some of the aspects of SLO, as well as Corporate Social Responsibility. It means the company is active in training and support for producers, support of local communities, sustainability of farming and harvesting, and environmental conservation, in their interest-area of red seaweed for production of carrageenan. Their stated aim is that, by 2025, 60% of their supply will be sustainable.

1.7.2 Market data

Foundation data for amounts and values of seaweed harvested and farmed can be obtained from FAO publications[217]. Although it is not possible to be comprehensive as not all activities or countries are reported, the output for 2019 is given as about 34.7 million tonnes of farmed seaweed and 1.1 tonnes of wild-harvested seaweed, about 3.1% of the total. For farmed seaweeds, the top 7 countries account for >99% and are all in Asia. The breakdown gives China at 58% of this, Indonesia next at 29%, South Korea at 5%, the Philippines at 4.3%, North Korea at 1.7%, Japan at 0.9% and Malaysia at 0.5%. By contrast, only 3 of the top 7 wild-harvest countries are Asian. The breakdown gives Chile 37%, China 16%, Norway 15%, Japan 6.4%, France 4.7%, Indonesia 4.1% and Peru 3.4%, a total of >87%.

Wet and dried seaweeds can command a range of prices: at-harvest price for British wet kelp is as little as €3.0-€3.5/kg wet weight, making each 100m longline worth €2900-€4100, but retail prices for a range of fresh or frozen seaweeds such as dulse (*Palmaria*, a red seaweed), kelp, sea lettuce (*Ulva*, green) and Sea spaghetti (*Himanthalia*, a brown seaweed) range from €25-€35/kg[218]. Economics of production still need to be achieved – the target production cost is probably €100 per tonne for commodity production, but current cost of farmed seaweeds is more like €500-€1000 per tonne.

[216] *Seaweed Revolution A manifesto for a sustainable future*

[217] *FAO Yearbook Fishery & Aquaculture Statistics 2019* FAO Rome 2021

[218] https://www.greenoceanfarming.com/buy-a-seaweed-farm.php

The market for seaweed-based products, mainly still hydrocolloids for food and packaging, but including soil fertilisers, soil remediation and higher-value streams, is projected to grow from c. €41 billion in 2020, 20% in Europe, to €89 billion by 2027[219]. Growth is seen as stimulated by the inclusion of seaweeds in sustainability and food security actions by UN and FAO. Dry seaweed materials formed almost 70% of the total market in 2020. Red seaweeds are expected to achieve 10% compound annual growth rate (CAGR) during the period. Hydrocolloids are expected to have highest growth rate in short-term, 13.5% per year 2018-2024[220].

EABA notes that global production of microalgae biomass is about 130,000 tonnes dry weight per annum worth about €2.6 billion, more than 75% from China; European output is <0.5% of global production and some countries such as the UK have virtually no industrial production of microalgae.

Data for microalgal production and industry economics are much more difficult to obtain and aggregate. The EU Report on the Blue Economy 2022 quotes FAO data for the value of declared microalgal production as minute in France and Bulgaria (5 tonnes worth €25,000) and rather more for Spirulina in France & Greece (c. 350 tonnes worth €8.5 million[221]).

Pure ingredients are more valuable, especially when usable as bioactives in nutraceuticals or para-medical products, or as purified laboratory reagents, but total markets are small or minute compared with hydrocolloids. Some of these, such as laminarins, are extractable from seaweeds only, others such as fucans and fucoidans, can be found in seaweeds and microalgae. The market for fucoidans is anticipated to grow from $36 million in 2021 to $46 million by 2028, a CAGR of 3.4%[222] and the combined fucoidans and beta-glucan markets by 8% CAGR during a similar period[223]. Sigma Aldrich sells 95%-pure fucoidan for £262 per 500mg[224], equivalent to over €600,000 per kg; and prices for fucoxanthin and astaxanthin of $15,000 per kg and $8,000-$10,000 per kg respectively have been noted[225].

In terms of amounts of using algae to absorb industrial by-products, one calculation looked at microalgae in the context of absorption of CO_2 generated by whisky distilleries in the UK[226]. Given an output of 755 tonnes CO_2 per million litres of spirits, this is equivalent to 600,000 tonnes CO_2 for this industry sector in UK. As each tonne dry weight of microalgae has absorbed 3-10 tonnes of CO_2, perhaps 60,000 tonnes DW of microalgae, or 550,000-600,000 tonnes wet weight, would be needed, almost 5 times current total production. Using microalgal biomass production to absorb CO_2 production is economically feasible only if plants are co-located with the industries producing them and take the CO_2 at no cost, as commercially-available CO_2 costs £100-£200 per tonne under normal circumstances in the UK but as high as £1000 per tonne in the 2021-2022 UK shortage.

1.7.3 Carbon and nutrient trading credits

The US DOE's **Bioenergy Technologies Office** (BETO) will put c. $19 million into technologies that use waste carbon to reduce greenhouse gas (GHG) emissions and produce reliable feedstocks for biotechnologies, in the program Carbon Utilisation Technology: Improving Efficient Systems for Algae. The USA has a target of producing at least 3 billion gallons of sustainable aviation fuels by 2030. The

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219 https://www.gminsights.com/industry-analysis/commercial-seaweed-market GMI1658 July 2021

220 www.alliedmarketresearch.com/seaweed-market A04296 May 2018

221 *The EU Blue Economy Report 2022* European Union ISBN 978-92-76-52444-1

222 https://www.marketwatch.com/press-release/fucoidan-market-insights-2022-with-top-leaders-growth-opportunity-with-341-cagr-share-and-growth-till-2028-2022-09-16 MarketWatch Sept. 16, 2022

223 https://www.mordorintelligence.com/industry-reports/beta-glucan-and-fucoidan-market

224 https://www.sigmaaldrich.com/GB/en/search/fucoidan-from-fucus-vesiculosus

225 S Boussiba, *pers. comm.*, EABA Workshop 2022

226 https://www.gov.uk/government/publications/biomass-feedstocks-innovation-programme-successful-projects/biomass-feedstocks-innovation-programme-phase-1-successful-projects Gold to Green to Gold project

two topic areas both allow algal projects: 1. Carbon utilisation efficiency from biomass- or atmospheric-based sources of CO_2 and 2. Algae-based technology to utilise anthropogenic CO_2 from utility and industrial sources. Given the carbon footprint of plastics alone, 2.2 billion tons of CO_2 equivalent in 2015, there is a pressing need for carbon neutral replacements.

China established a pilot scheme for CTCs (Carbon Trading Credits) in January 2022. The new marine **carbon sink trading platform** at the Xiamen Carbon and Emissions Trading Center processed 15,000 tonnes-worth of seaweed carbon credits for CNY 12 million (€1.6 million)[227]. The Ministry of Agriculture and Ministry of Natural Resources are officially supporting the pilot scheme, and local officials anticipate nearly CNY 1 billion (€136 million) for carbon sequestration credits from local algae and shellfish cultivation if the pilot is successful. The absence of a global standard for measuring and certifying carbon sequestration in fisheries and oceans currently prevents establishing the same regimes as for terrestrial forests.

> The economic values of the environmental/societal services of extractive species should be recognised and accounted for in the evaluation of the full value of these IMTA components. Seaweeds and invertebrates produced in IMTA systems should be considered as candidates for nutrient/carbon trading credits.
>
> *Source: Chopin et al. (2012)*

The champion of Nutrient Trading Credits (NTCs) is Thierry Chopin, who consistently points out in his studies of IMTA that more money can be made through NTCs than CTCs (Carbon Trading Credits)[228]. The global seaweed sector's NTCs could be worth between €1.14 billion-€3.42 billion for nitrogen and €53 million for phosphorus, while CTCs would be worth around €30 million. At the 2021 United Nations Climate Change conference (COP26), seaweeds were talked about as an ocean-based tool for offsetting both climate change and increased nutrition needs[229].

On a similar note, in the US Greenwave, has set up the Kelp Climate Fund[230], a programme with the goal of compensating kelp farmers for the climate benefits of their crop. Participating farmers are paid $1 for every foot of kelp seed they outplant. This value is based on a recent NOAA and The Nature Conservancy study that calculated the market value of the ecosystem services that seaweed and shellfish farming provide[231].

1.7.4 Investment

Apart from the investment of the EU in trans-national collaborative projects in Framework and Horizon programmes, commercially-orientated and private investment programmes are needed for realisation of the full potential of algae. The EU's BlueInvest initiative[232] (which also promotes innovation in aquaculture) will continue to bring together investors and entrepreneurs. A financial instrument will be set up with EMFAF (European Maritime, Fisheries and Aquaculture Fund 2021-2027)[233] and InvestEU[234] contributions and will also be available to support investment in sustainable aquaculture activities and

[227] https://www.seafoodsource.com/news/aquaculture/china-completes-first-carbon-credits-trade-from-aquaculture-sequestration-pilot M Godfrey Jan 18 2022

[228] Chopin T, Cooper JA *et al.* (2012) Open-water integrated multi-trophic aquaculture: environmental biomitigation and economic diversification of fed aquaculture by extractive aquaculture *Rev Aquacult* 4: 209-220 doi: 10.1111/j.1753-5131.2012.01074.x

[229] https://thefishsite.com/articles/seaweed-aquaculture-panacea-or-hype-imta N Holmyard 6.4.22

[230] https://www.greenwave.org/methodology

[231] Barret, L.; Theuerkauf, S.; Rose, J.; Alleway, H.; Bricker, S.; Parker, M.; Petrolia, D.; Jones, R. 2022. Sustainable growth of non-fed aquaculture can generate valuable ecosystem benefits. Ecosystem Services. 53: 1 - 16.

[232] https://webgate.ec.europa.eu/maritimeforum/en/frontpage/1451

[233] https://oceans-and-fisheries.ec.europa.eu/funding/emfaf_en

[234] https://investeu.europa.eu/index_en

technologies. EU Member States can also use funds under the future EMFAF to support investments in innovative solutions by the EU aquaculture sector.

Some investment and accelerator organisations focus on aquaculture, marine opportunities and algae. One example is Hatch[235], set up specifically to support entrepreneurial actions in innovative farmed and alternative seafoods, with small environmental footprints. Relevant companies in its portfolio include AI and smart monitoring developers ANB Sensors, Blue Lion Labs and alga producers and processors Symbrosia (seaweed feeds for methane reduction in ruminants), Kuehnle (new fermentation processes for astaxanthin), Brilliant Planet (carbon sequestration via open-pond microalgae) and OceanFarmr (digitised farm management systems). Another is Blue Bio Value Acceleration[236]. Supported by the Oceano Azul and Calouste Gulbenkian Foundations, this operates an Acceleration programme with mentors for start-ups, many oof which are algae-focused[237], and an annual selection of prizewinning ideas.

Individuals have also started to invest via their funding vehicles. The Bezos Earth Fund has created The Seaweed Solution program[238] to "drive increased public acceptance of seaweed as a climate solution and increases in demand for animal feed, proteins, and biodegradable packaging, resulting in significant greenhouse gas reductions [and set] the stage for large scale seaweed farming that could deliver transformational climate benefits." This has over 24 partners including Alaska Fisheries Development Foundation, Oceanium Ltd, Global Seaweed Coalition, Ocean Rainforest, Woods Hole Oceanographic Institute and the WWF, who are co-ordinating the $10.65 million funding.

The web-site of Phyconomy[239] is extremely useful for looking at current investments in seaweeds. In 2020-April 2022, 58 deals were recorded, with 34 in 2021 at a value of $168 million. Nordic Seafarm intended to use its funding of €2 million to "become the largest seaweed company in Europe for plant-based foods from the ocean" and the US Atlantic Sea Farms was going to use its $3.1 million for a new kelp-processing plant, taking fresh harvests from a large number of small suppliers in its cooperative[240]. Alginor gained the largest amount, $33 million, for development and marketing of seaweed ingredients for pharmaceuticals and nutraceuticals. Investment patterns are a guide to value-chain trends, suggesting that seaweed-based plastics are likely to expand greatly in the near-future, with >35 investments to-date. More recently, in 2022 the Indian seaweed-to-biofuels company Sea6 Energy closed a Series B $18.5M funding from BASF, Aqua-Spark & Tata.

Phyconomy also assesses dynamics in the seaweed sector, noting that most of the wild harvesting companies have not started commercial activities, and are aiming to harvest *Sargassum* and other nuisance algae. Their free-access database of over 1200 companies includes producer associations and policy organisations as well as production, processing and engineering companies. 935 entries lack production data and 76 are recorded as 'not started yet'. Extracted data is summarised below.

Table 1.2: Profile of seaweed production and processing companies

	size of farm or processing total, tonnes per year					
	0-10	**10-100**	**100-1000**	**1000-10,000**	**10,000-100,000**	**100,000-1,000,000**
number of companies	89	57	39	26	20	6

Source, Phyconomy 2022 https://phyconomy.net/database/

235 https://www.hatch.blue

236 https://www.bluebiovalue.com/acceleration/acceleration-2021

237 https://www.bluebiovalue.com/startups/

238 https://www.bezosearthfund.org/our-programs

239 https://phyconomy.net/

240 https://thefishsite.com/articles/seaweed-aquaculture-panacea-or-hype-imta N Holmyard 6.4.22

The 6 in the top bracket include 3 Chinese companies, Leili, BLG/Shanghai Brilliant Gums and Qingdao Brightmoon SW Group, Olmix France, Gelymar Chile and Oceana Minerals Brazil. 11 European companies are in the 10,000-100,000 tpa category; of the total in the database, European entries are 36%.

Table 1.3: Profile of seaweed companies by country

Europe		Rest of world	
total	443	total inc. some not shown	779
United Kingdom	90	United States of America	158
France	70	China	113
Ireland	50	Japan	109
Norway	48	Australia	52
the Netherlands	45	Indonesia	49
Spain	26	South Korea	42
Denmark	22	Philippines	39
Germany	21	Canada	32
Portugal	18	New Zealand	23
Sweden	12	Chile	19
Iceland	10	India	18
Belgium, Italy @5	10	Mexico	17
Estonia, Finland, Switzerland @4	12	South Africa	14
Austria, Faroes, Greenland, Lithuania, Slovenia @1-3	9	Tanzania	13

Source, Phyconomy 2022 https://phyconomy.net/database/

1.8 Recommendations for supporting technology innovation

The Lloyd's Register Foundation, in its Manifesto[241], pinpointed the opportunities that would accelerate the growth of algal activities: development of Carbon Schemes providing compensation for eco-services to algal activities; a Safe Seaweed Coalition to move forward on restoration of habitats and production of pilot standards and safe operation protocols; and a Global Blue Farming Platform that would encourage "market mapping initiatives" to support sustainable private/public investments. The Platform would also:

- facilitate science, private sector and government coordination and collaboration to effectively share knowledge and drive measurable action (Target 1);
- provide a business-to-business finance platform (Target 2);
- advance the use of "blue farming" to create a way by which universities and technical colleagues can market new degrees/diplomas and create an identity and a sense of pride for people engaged in the blue farming industry, across e.g. primary production, genetics and breeding, economics, crop systems etc. (Target 3);
- and develop regional centres of excellence to provide subject experts to do outreach and training, and engage in cross fertilisation across regions (Target 4).

The Manifesto also recognises that to achieve offshore seaweed production needs design and deployment of new types of anchors, buoyancy systems, ropes, harvesting vessels and transportation methods, potentially specific to each type of seaweed. To develop innovation and experience in offshore production, pilots need to be established. Biorefinery systems need to be developed and piloted ('ideally in the ocean', to avoid the cost of transporting wet seaweed) in order to extract the various seaweed compounds into different sub-products for multiple and higher value applications to maximise resilience and profits for production.

[241] *Seaweed Revolution A manifesto for a sustainable future* Lloyd's Register Foundation

These have started to happen, and the EU Algae Initiative has put forward many suggestions for action to accelerate progress in Europe. There is a consensus on action seen in proposals and recommendations by the other interest groups and initiatives mentioned in this chapter. Success however depends on how willing individual Member States are to adapt existing disparate approaches and practices to a Europe-wide vision of what might be needed.

- For microalgae and seaweeds, the extreme upstream end of the organisms themselves still requires support of science and investigation - genomics and production of starting cultures, including breeding and seeding for seaweed, are crucial and require accelerating, with establishment of libraries and biobanks and open access annotated gene sequences. The volume of seaweed hatcheries will need significantly increasing to satisfy demand.
- Supporting the wider use of practical genetics will definitely produce useful results. The ability to manipulate the genomes of microalgae using CRISPR technology has already resulted in enhanced omega-3 fatty acid production and biomass growth[242] and in availability of contract CRISPR services for algae[243]; CRISPR has also been used in *Ulva* for gene-editing[244] and is in use at CNRS Roscoff for gene editing in *Ectocarpus* and kelp. DNA methylation is a topic under research e.g. at CNRS Roscoff, since it is an important aspect of stress tolerance in algae; in seaweed, epigenetic DNA methylation patterns are heritable and transferred via the sporophyte.
- Life cycle assessments (LCAs), life cycle sustainability assessments (LCSAs) and Carbon and Nutrient Balance Analyses at the planning stages of microalgae and seaweed aquaculture are critical to validating production projects.
- For seaweeds, there are at the same time moves to deeper-water and on-land cultivation, with a greater need for automation, process management, real-time monitoring and remote responses.
- For microalgae, the moves are to:
  - advanced photobioreactors designed to give more precise control of all parameters including light penetration and energy efficiency;
  - systems for tuning light wavelengths to provide not only optimum growth-rate but also drive production of desired components;
  - porous film substrates;
  - use of mixotrophic or heterotrophic organisms;
  - consortia of microbes that enhance efficiency and growth.
- For biomass management, whether seaweed or microalgae, the future is in wet biomass processing where possible.
- In biorefineries, there will be milder and milder and less-and-less energy-intensive processing steps, often now using sophisticated technologies such as nanopulse electric fields, ultrasound and acoustic wave separations.
- In extraction processes, microwave-enhanced extraction, ionic liquids and non-toxic Deep Eutectic Solvents will take over from acid-alkali, toxic organic and more costly extraction methods.

[242] Patel VK, Soni N *et al.* (2019) CRISPR-Cas9 system for genome engineering of photosynthetic microalgae *Mol Biotechnol* 61(8): 541-561 doi: 10.1007/s12033-019-00185-3

[243] e.g. https://www.lifeasible.com/genome-editing-in-microalgae-through-crispr-technology/

[244] Ichihara K, Yamazaki T and Kawano S (2022) Genome editing using a DNA-free clustered regularly interspaced palindromic repeats-Cas9 system in green seaweed *Ulva prolifera Phycol Res* 70: 50-56 doi: 10.1111/pre.12472

In the context of LCAs and econometric analysis, the work of the International Energy Authority's Bioenergy Task 42 is important for biorefinery validation. BT42 "provides an international platform for collaboration and information exchange between industry, SMEs, Governmental Organisations, NGOs, Research & Technology Organisations and universities concerning biorefinery research, development, demonstration and policy analysis"[245]. It has developed a Biorefinery Complexity Index BCI[246]. In the absence of data from large-scale industrial units, BCI combines testable features and performance of different pilot, bench-top or small-scale systems to allow comparison of technical and economic risks of different approaches. With respect to algal biorefineries, analysis of the BCI of different systems supports the trend to using heterotrophic or mixotrophic organisms and a range of target outputs, including higher-value extractives such as food and dietary products and pharmaceuticals as well as larger-scale commodity products such as fuels and fertilisers, where market prices currently make mono-directional algal processing uneconomic.

The abilities of macroalgal and microalgal systems to remove undesirable chemical and biological contaminants should continue to be validated by establishing pilot or demonstration plants at scale-up levels – microalgae as adsorbents and metabolisers of pollutants in the input streams and seaweeds as suppressors, by nutrient competition, of toxic microalgae in marine eutrophication and for other aquaculture activities such as mussel farming.

The aims of circularity and carbon-reduction are being tackled on-land by linkage of nutrient outputs from other production, processing and wastes-management industries to microalgal and macroalgal biomass production, which is feasible in the current state of technology advancement, given efficient management of design, including modular processing units, linkage of sources of inputs to algal production units, including effective co-location and permissive or at least flexible regulations and permit systems. The major challenges here are:

- to understand how to process potentially-harmful components out, such as heavy metals and arsenic, spoilage organisms, microalgal toxins, excessive iodine etc, and make safety of the end-products inherent and implicit;
- to re-define wastes so they can actually be used as inputs;
- to ensure that LCAs and other econometric and functional analyses are detailed-enough and contain accurate data to be trustworthy.

The national and EU-wide definitions of wastes limit the use of algae in the Circular Economy as nutrient and CO_2 absorbers. This is a complex issue. The absolute change would be a recognition that it does not matter what the origin is of the algal biomass or the inputs into the process provided that the process has been validated as producing something safe, or the outputs/end-products have monitorable criteria for acceptance that means they are independent of the sources of inputs. This would allow the use of solid, liquid and gaseous waste outputs from any industry without changing a raft of legislation covering each sector or type of output. Annexes of derogation could be put in place for EU Regulations dealing with existing categories of waste (for example animal by-products or food business wastes), so that MSs will transpose them into national law. Work is already being done on acceptability criteria for algal biomass via standards, which will help this process.

At sea, seaweed sinking is a 'hot topic' - the concept of growing or collecting seaweed at a massive scale and sinking it to the ocean bed. Several companies have large-scale claims for what their projects and plans will achieve, if funded, but there are also sceptics, basing their position partly on the sheer scale of seaweed farming or collection needed if there is to be a useful impact on anthropogenic carbon production, partly on grounds of unknown and currently unmeasurable environmental impacts, and

[245] https://task42.ieabioenergy.com/

[246] van Ree R, Jorgensen H et al. 2014 The Biorefinery Complexity Index https://task42.ieabioenergy.com/wp-content/uploads/sites/10/2017/06/BCI-working-document-20140709.pdf includes a specific microalgal biorefinery example

partly on realistic alternative uses which have demonstrable environmental benefits, such as production of biochar as a soil restorer. Ocean-sinking is however an appealing option for groups who want to see a fast response to the situation, at political level.

For other algal developments, the single major stumbling block is the broad span of regulation covering algae, which limits the access of farming and harvesting to crop agricultural support regimes and allows production, processing, co-location and other activities to be subject to uncoordinated and incoherent systems of sea- and land-based legislation, permits and licensing operated by differing farming, fishing, marine spatial use and land-zoning authorities across the EU. Options could include sea-zoning, with allocation of parcels for seaweed farming as in the Faroe Islands, or recognised rotational permits as in Norway, or pilot test-site permits, as in the Netherlands. All wind-farm permits should include prevision of 'Wind+Weed', if necessary as part of a broader Multi-Use plan. At a practical level, the safety validation framework for food needs adapting for seaweeds and algal products as or in food, to reflect reality of human risk more closely, and a framework needs establishing for biochar from biomass. The topic of regulatory de-complexing for algal developments requires a more detailed analysis than is possible here, but all bodies involved from Industry to European Commission via others such as EABA and EU4Algae recognise it as a critical issue and are addressing it.

The interview-based survey carried out as part of the Interreg project EnhanceMicroalgae included attention to the difficulties of regulation for food ingredients and foods coming from microalgal species not on a QPS (Qualified Presumption of Safety) or Novel Foods list[247]:

- With regard to species, an improvement would be that the European Commission identify 20–30 species and state the conditions in which they must be grown to reach the toxicological quality required by the EU.
- Starting from this biomass, extracts could be authorised for novel food production and commercialisation.
- By creating a standard operating procedure, companies wishing to introduce new microalgae and related products in the market would also be informed about the mandatory toxicological, genetic and physiological analyses and could select species among a list of 20 to 30 already authorised species.
- And subsequently, a suggestion that commercial companies collaborate on funding the baseline toxicology studies as a benefit for the whole industry.

So, many recognised problems, some policy-produced and others relating to the difficulty of aligning feasible, economic technologies with value-chains and market attractiveness, many potential actions for which there is a great consensus and, in Europe, a blueprint in the Algae Initiative for moving forward, and many opportunities for technology advancement to achieve this.

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[247] Rumin J, Gonçalves de Oliveira Junior R *et al.* (2021) Improving Microalgae Research and Marketing in the European Atlantic Area: Analysis of Major Gaps and Barriers Limiting Sector Development *Mar Drugs* 19: 319 doi: 10.3390/md19060319; for the QPS list itself, which includes the microalgae *Tetraselmis*, *Euglena*, *Haematococcus* and *Schizochytrium*, used for production purposes only, see https://zenodo.org/record/6902983#.Y5SNMHbP2M8; for the consolidated novel foods list, which includes products derived from these 4 and *Schizochytrium* strains, plus *Ulkenia* and *Odontella*, see https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02017R2470-20220829&from=EN

2 FOCUS ON SARGASSUM

*Chapter authored by Antoine Erwes and Nicolas Erwes

2.1 Introduction

The coastlines of the European Union's (EU) Overseas Countries and Territories (OCT) have been subject to unpresented and growing influxes of macroalgae since 2011. In the global context of environmental disruption, the proliferation of macroalgae accelerates the loss of habitat-forming species and may lead to significant changes in the functioning of ecosystems and human coastal economies. Similar to the recent development of macroalgal blooms in China, the increasing golden tides of Sargassum in the Atlantic region could be ecological indicators of large-scale, oceanic eutrophication.[1] The purpose of this report is to examine the impact of Sargassum influxes, with a specific focus given to the holopelagic species found in the Atlantic area. After providing an overview of the main Sargassum species which impact the EU, this paper will provide an overview of the phenomenon, investigate its causes and consequences, before identifying its main applications which have emerged. Finally, recommendations will be formulated to explain how the valorisation of this abundant biomass can render Sargassum tides into an economic opportunity and concurrently solve their associated environmental problems.

2.2 Characteristics

2.2.1 Origins

Fossil records of Sargassum date back to the Tethys Sea, with Jerzmańska and Kotlarczyk having found "numerous brown algae together with fish skeletons from the Oligocene (33,9 to 23,03 million years ago) in the Polish Carpathians."[2] The authors identified air bladders structures inserted on branches in fossils that resembled the modern Sargassum. On an anthropogenic scale, Sargassum have been documented and used by different civilisations around the world. Pérez-Rubin Feigl's study "*Las algas y los antiguos navegantes españoles*"[3] first mentioned how the inhabitants of North America already knew of Sargassum, with ancient Mayans referring to the bioresource "u tail kaknab" which means "thrown by the lady of the sea."[4] European awareness about Sargassum formally emerged after Christopher Columbus' voyage to the Americas, during which ships were entrapped in floating algal masses due to the lack of wind. The etymological origins of the term are uncertain but seem to have been inspired by a variety of grapes called "salgazo" in Portuguese vineyards, progressively deriving into "sargaçao."[5] Alternatives point towards the ancient Spanish word "algaço" used to describe

[1] B Lapointe, R Brewton, L Herren, M Wang, C Hu, D McGillicuddy Jr, S Lindell, F Hernandez, and P Morton, "Nutrient content and stoichiometry of pelagic Sargassum relects increasing nitrogen availability in Atlantic Basin", *Nature Communications* 12:3060 (2021), https://www.nature.com/articles/s41467-021-23135-7

[2] Anna Jerzmańska and Janusz Kotlarczyk, "The beginnings of the Sargasso assemblage in the Tethys", *Paleogeography, Paleoclimatology, Paleoecology,* 20:4 (November 1976), https://www.sciencedirect.com/science/article/abs/pii/0031018276900092

[3] Juan Rubin, "Las algas y los antigos navegantes espanoles 1492-1792", *Instituto Espanol de Oceanografia* 25 (June 2016), https://www.researchgate.net/profile/Juan-Rubin/publication/309242378_Las_algas_y_los_antiguos_navegantes_espanoles_1492-1792/links/58071e0e08ae0075d82c7c0e/Las-algas-y-los-antiguos-navegantes-espanoles-1492-1792.pdf

[4] José Luis Godinez-Ortega, Juan Cuatlan-Cortes, Juan Lopez-Bautista and Brigitta van Tussenbroek, "A natural history of floating Sargassum species (Sargasso) from Mexico", in *Natural History and Ecology of Mexico and Central America* (London: IntechOpen, 2021), https://cdn.intechopen.com/pdfs/76196.pdf, 2.

[5] Godinez-Ortega et al, "A natural history of floating Sargassum species (Sargasso) from Mexico", 2.

alginates or the willow trees (morphologically similar to Sargassum), colloquially known in Spanish as "sarga."[6]

2.2.2 Classification

Sargassacae is a genus or family of brown macroalgae from the order Fucales that includes over 360 species distributed across the world in both temperate and tropical oceans. It is the most diverse genus of marine macrophytes and Sargassum species have a high degree of morphological complexity and plasticity. According to Yip et al, "Sargassum has a characteristic non-filamentous thallus with a holdfast that branches to form many main axes" and have "distinct leaves, receptacles, and the vesicles which are found on the axes near the leaves keep the algal structure upright when submerged."[7] Sargassum species typically have hollow berrylike floats (pneumatocysts) that are filled mostly with oxygen aiding the buoyancy of the plant.[8] The four Sargassum subgenera (S. subgen. *Arthrophycus*, *Bactrophycus*, *Sargassum* and *Phyllotrichia*) are now subdivided into a total of 12 sections and further subdivisions were abandoned.[9]

The identification of the species is difficult due to their polymorphic nature, phenotypic diversity in response environmental change, age, and reproductive state. This variation can be large enough for a single species to be mislabelled as two or more species.[10] Traditional classification efforts have focused on "the blade morphology, the margins of the blades, the pneumatophores (air bladders), the branching, and the degree of morphology of the reproductive organs."[11] These bladders keep the Sargassum afloat and allow their blades undergo photosynthesis.[12] The recent application of Deoxyribonucleic Acid (DNA) sequencing tools has supplemented these findings with molecular databases. The use of genetic markers to reconstruct the phylogenetic history of a species "has helped to resolve species relationships and identifications for many regions. Most species are benthic (attached to rocks or other substrates) and two are described are holopelagic (spend their entire life cycle floating in the open ocean, transported with the influence of ocean winds and currents).[13] This report will focus on the three main invasive species of Sargassum, one benthic (*Sargassum muticum*) and two holopelagic (*Sargassum natans* and *Sargassum fluitans*).

[6] Daniel Robledo, Erika Vazquez-Delfin, Yolanda Freile-Pelegrin, Roman Manuel Vasquez-Elizondo, Zujaila Nohemy Qui-Minet and Adan Salazar-Garibay, "Challenges and opportunities in relation to Sargassum events along the Caribbean Sea", *Frontiers in Marine Science* 8 (22 July 2021), https://www.frontiersin.org/articles/10.3389/fmars.2021.699664/full

[7] Zhi Ting Yip, Randolph Quek, Jeffrey Low, Bryan Wilson, Andrew Baumann, Loke Chou, Peter Todd and Danwhei Huang, "Diversity and phylogeny of Sargassum (Fucales, Phaeophycae) in Singapore", *Phytotaxa* 369:3 (September 2018), https://www.researchgate.net/profile/Andrew-Bauman/publication/327751047_Diversity_and_phylogeny_of_Sargassum_Fucales_Phaeophyceae_in_Singapore/links/5ba847ac299bf13e6047d0aa/Diversity-and-phylogeny-of-Sargassum-Fucales-Phaeophyceae-in-Singapore.pdf, 1.

[8] The Ocean Foundation, "Sargassum Factsheet: Scientific Information", (December 20, 2019), https://oceanfdn.org/wp-content/uploads/2020/03/Sargassum-Scienctific-Factsheet.pdf

[9] Lydiane Mattio and Claude Payri, "190 years of Sargassum taxology, facing the advent of DNA Phylogenies", *The Botanical Review* 77:1 (March 2011), https://www.proquest.com/openview/b5d7c92f292567ea5757dac184c76c3f/1?pq-origsite=gscholar&cbl=41407

[10] Yip et al, "Diversity and phylogeny of Sargassum (Fucales, Phaeophycae) in Singapore", 1.

[11] Godinez-Ortega et al, "A natural history of floating Sargassum species (Sargasso) from Mexico", 9.

[12] Koffi Komoe, Yacouba Sankare, Guessan Bra Yvette Fofie, Abou Bamba, Abraham Sahr, "Taxonomic study of two species of Sargassum: *Sargassum fluitans* (Børgesen) Børgesen and Sargassum natans (Linnaneus) Gaillon (brown algae) collected in Côte d'Ivoire coasts, West Africa", *Natural Science* 14:10 (2016), http://www.sciencepub.net/nature/ns141016/09_30921nsj141016_50_56.pdf , 24.

[13] The Ocean Foundation, "Sargassum Factsheet: Scientific Information".

2.2.3 Reproduction

Benthic species reproduce sexually. Female oogonia are exposed outside the conceptacle (a cavity immersed in the surface of the thallus with an opening to the outside that contains the reproductive structures).[14] Fertilisation occurs once the sperm is chemically attracted to the oogonium, and the zygote is released from the receptable driven by light and temperature cues.[15] The young thalli of benthic Sargassum then come into contact with a solid substrate, on which they will produce rhizoids and growing axes. Unlike their benthic counterparts, clonal reproduction is the only mechanism of propagation known for holopelagic species today.[16] This occurs by fragmentation of the old thalli sections that break apart, allowing for newly formed fragments to grow again. It is worth noting that some benthic species, such as the invasive *S. muticum*, are capable of reproducing both sexually and by fragmentation.[17] The fronds can continue to shed germlings if they are detached and this powerful dispersal mechanism explains the invasive success of the species.

2.2.4 S. muticum

This large brown seaweed is native to the Western Pacific, spanning from China to Russia. Also known as Japanese wire weed, *S. muticum* is now considered an invasive species in most parts of the world, having spread to the Eastern Pacific (Alaska to Mexico), the Eastern Atlantic (Morocco to Norway), and the Mediterranean through imported Japanese oysters.[18] The seaweed is composed of two distinct parts:

> "the perennial, dark brown basal axes, and the lighter coloured annual primary laterals. The latter are shed or torn off in the late summer. During the summer, the number of small round vesicles (air bladders) increases. Receptacles are most abundant in early autumn."[19]

While the EU does not consider any Sargassum species as invasive species (in such a case the Invasive Alien Species regulation requires "a set of measures to be taken across the EU" to tackle this seaweed)[20], most Member States impacted by *S. muticum* have classified this species as invasive (Germany, France, Ireland, Spain, Belgium, Netherlands). This species of Sargasssum is highly adaptive to different environmental parameters, such as desiccation, full sunlight exposure, variations in salinity and temperature. This enables the species to occupy a broad range of habitats, "from upper intertidal rock pools to the subtidal and substrata to eel-grass beds."[21] The species can therefore grow over a wide range of latitudes, from temperatures below 0°C in Norway and Sweden to 30°C in the Venice lagoon. *S. muticum* is usually between 1 and 3 meters in length, but can grow to 16 meters in certain habitats (notably in French Britany and Normandy). Also a benthic species which can live up to depths

[14] Godinez-Ortega et al, "A natural history of floating Sargassum species (Sargasso) from Mexico", 14.

[15] Zhourui Wang, Feijiu Wang, Xiutao Sun, Wenjung Wang, Fuli Liu, "Reproductive biology of Sargassum thunbergii (Fucales, Phaephycae)", *American Journal of Plant Sciences* 5:17 (January 2014), https://www.researchgate.net/publication/273431877_Reproductive_Biology_of_Sargassum_thunbergii_Fucales_Phaeophycеае

[16] Godinez-Ortega et al, "A natural history of floating Sargassum species (Sargasso) from Mexico", 17.

[17] Michael Guiry, "Sargassum muticum wireweed", *Seaweed Site: information on marine algae*, accessed 2 December 2022, https://www.seaweed.ie/sargassum/

[18] Britannica, "Sargassum : genus of brown algae", accessed 2 December 2022, https://www.britannica.com/science/Sargassum

[19] Guiry, "Sargassum muticum wireweed"

[20] European Commission, Directorate General for Environment, "Invasive Alien Species", accessed 2 December 2022, https://ec.europa.eu/environment/nature/invasivealien/index_en.htm

[21] European Commission, Directorate General for Environment, "Invasive Alien Species"

of 20 meters, it can also form floating mats on the surface of the sea. It can grow up to 10 cm a day and has a life span of 3 to 4 years[22].

Figure 2.1: *Sargassum muticum*[23]

2.2.5 S. natans and S. fluitans

The genus is found in temperate and tropical latitudes all around the world (except for Antarctica). The largest concentrations of holopelagic Sargassum naturally occur in the Atlantic Ocean. These specimens can measure up to 1 metre but are usually between 20 and 30 cm in length 20 to 30 cm wide. While individuals of these species may occasionally float alone, they more often tangle together to form communities which resemble large rafts or "windrows". Knowledge of growth and mortality rates is limited, but its biomass is known to increase very quickly under the right conditions (nutrients, salinity and temperature).[24] Holopelagic Sargassum exhibit higher growth rates in higher temperatures (until 30°C) and cannot survive in waters below 18°C.[25] They usually have low productivity and a bright yellow colour, typical of nutrient depleted populations. Neritic populations (closer to the coast), which have greater availability of nutrients (mainly nitrogen and phosphorous), develop a deeper brown colour, attaining higher photosynthetic capacity and productivity.[26]

The observed influxes of Sargassum in the Caribbean region consist predominantly of three species of holopelagic sargassum: *S. natans I and S. fluitans III* being the most common, and *S. natans VIII* being a typically rare form. Although there are no genetic differences between these species, their various morphotypes has stirred debate as to whether there may be a third additional distinct species.[27]

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[22] Guiry, "Sargassum muticum wireweed"

[23] Image taken from SCRIPPS Institution of Oceanography, "Invasive Seaweed on the San Diego Coast", accessed 2 December 2022, https://coralreefecology.ucsd.edu/research/seaweed-research/

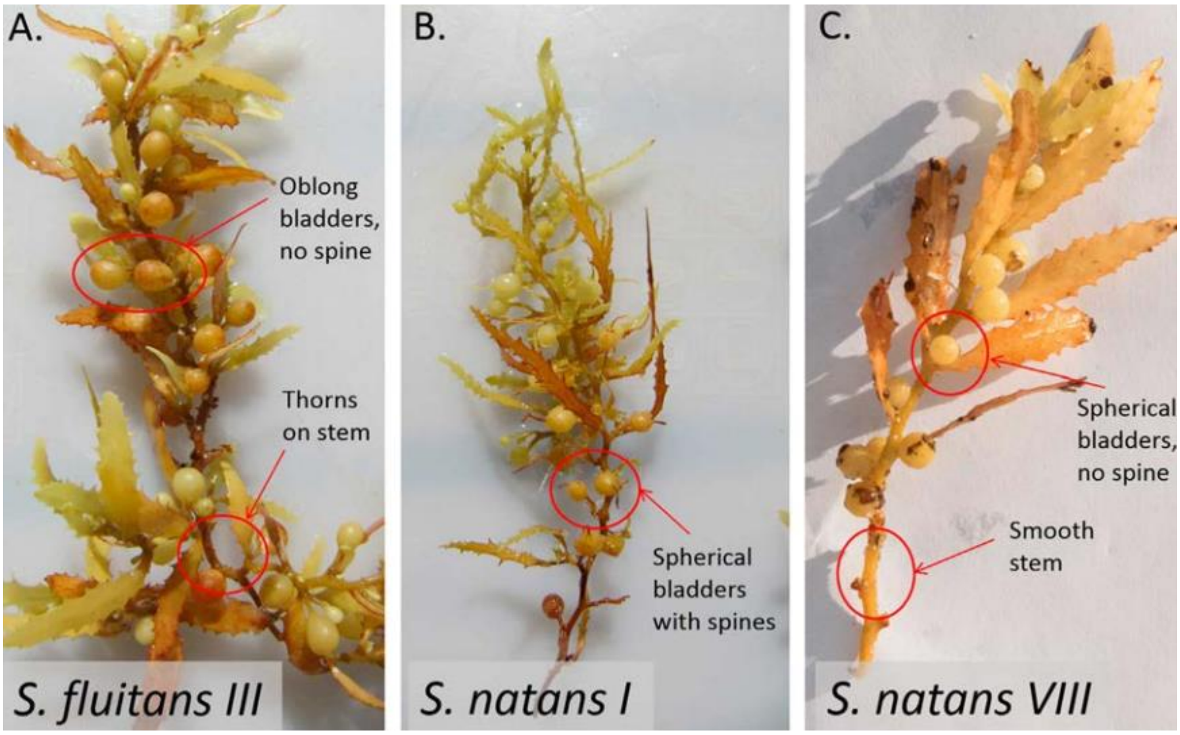
[24] Anne Desrochers, Shelly-Ann Cox, Hazel Oxenford, and Brigitta van Tussenbroek, "Sargassum Uses Guide: a resource of Caribbean researchers, entrepreneurs, and policy makers", *Centre for Resource Management and Environmental Studies (CERMES),* (October 2020), https://www.cavehill.uwi.edu/cermes/projects/sargassum/docs/desrochers_et_al_2020_sargassum_uses_guide_advance.aspx , 9.

[25] Godinez-Ortega et al, "A natural history of floating Sargassum species (Sargasso) from Mexico", 18.

[26] Ibid, 18.

[27] Desrochers et al., "Sargassum Uses Guide: a resource of Caribbean researchers, entrepreneurs, and policy makers", 3.

Figure 2.2: *Sargassum natans and fluitans*[28]



S. natans is a bushy seaweed with narrow leaf blades which are golden brown with toothed edges. The rubbery-textured leaves range from 2 to 6 mm wide and 2 to 10 cm long. The gas-filled floats are less than 6 mm in diameter and are held on short stalks along the stems among the leaves. The floats of *S. natans* have a single protruding spine 2 to 5 mm long, but there is no single main stem. It grows in many directions forming clumps that can reach 60 cm long. It is these clumps that form together into much larger mats. *S. fluitans* very much resembles *S. natans*, as both are golden brown in colour, with toothed, rubbery leaves, small gas-filled floats and no central stem. The leaves of the "broad-toothed Gulfweed" are wider, reaching up to 8 mm wide and 2 to 6 cm long. The gas bladders of *S. fluitans* are held on relatively long stalks along the centre of the plant. The surface of the floats is smooth.

The specific composition of holopelagic Sargassum varies regionally. Garcia-Sanchez et al's 2020 study found that:

- 87% of the Sargasso Sea is composed of *S. natans I;*
- 87% of the Atlantic Ocean East of Caribbean is composed of *S. natans VIII;*
- 60% of the total wet biomass in the entire region was composed of *S. fluitans III;*
- *S. natans VIII* decreased between 2016 and 2019 but increased again in 2020;
- *S. natans I* nearly absent between 2015 and 2017, appeared in 2018 when it compromised 23% of total wet biomass, and continued to increase in relative abundance since.[29]

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[28] Image taken from United Nations Environment Programme – Caribbean Environment Program, "Sargassum White Paper: Turning the Crisis into an opportunity", (2021), https://wedocs.unep.org/bitstream/handle/20.500.11822/36244/SGWP21.pdf

[29] Marta Garica-Sanchez, Caroline Graham, Elisa Vera, Edgar Escalante Mancera, Lorenzo Alvarez Filip, Brigitta van Tussenbroek, "Temporal changes in the composition and biomass of beached pelagic Sargassum species in the Mexican Caribbean", *Aquatic Botany* 167 (October 2020), https://www.sciencedirect.com/science/article/abs/pii/S0304377020300851?dgcid=rss_sd_all&utm_campaign=RESR_MRKT_Researcher_inbound&utm_medium=referral&utm_source=researcher_app

The authors suggested that these variations could be explained by the multiple origins of sargasso or may reflect environmental conditions in the seas where they passed through, since sargasso species have different thermal tolerances and growth rates.[30] When light, nutrient, and temperature conditions are favourable, the maximum doubling time for *S. fluitans* is 9,3 days and 13,8 days for *S. natans*.[31]

2.3 Case study: holopelagic blooms in the Atlantic region

2.3.1 Overall situation and trends

Holopelagic sargassum is not new in the Atlantic region, but the growing recurrence of blooming events is only a decade old phenomenon. The highest concentrations of Sargassum in the region used to be in the Sargasso Sea, in the subtropical clockwise circulating gyre in the North Atlantic, delimited by the Gulf Stream on the western edge, the North Atlantic Current in the north, the Canary current in the east, and the North Atlantic Equatorial Current in the south. The accumulation of Sargassum could be massive, completely segregated, distributed into small patches, or along lines due to the Langmuir circulation.[32] Small or occasionally larger quantities of sargasso have always been arriving intermittently to the coasts of the Caribbean and Gulf of Mexico through the "Sargasso Loop System" through which the algae from the Sargasso sea is transported southwards due to high pressure anomalies.[33] These seaweed then acquire nutrients upon entering the nutrient rich Gulf of Mexico. Godinez-Ortega's study suggests that "there appears to the a neritic- ocean coupling in this loop system which facilitates the adaptation of sargasso to large differences in nutrient availability, maintaining population in oligotrophic waters but rapidly responding to increasing nutrients when available."[34]
Wang et al's study indicated that "the entire monthly sequence of Sargassum abundance distributions shows that from 2000 to 2010, the Central Atlantic showed very low abundance, with occasional quantities near the Amazon River mouth from August to November."[35] The first massive Sargassum bloom in the Central Atlantic started in 2011. Research into the causes of this the recent massive influxes of sargassum led to the identification of a new 'consolidation region' in the Tropical Atlantic, between the Gulf of Guinea and the north coast of Brazil that is generally agreed to be the source of the influxes to the Caribbean and West Africa.[36] This new area of concentration has been named the Great Atlantic Sargasso Belt (GASB).[37] While multiple sources of Sargassum may exist, the shape of the GASB is consistent with advection by the ocean circulation patterns in the tropical Atlantic.[38]

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[30] Garica-Sanchez et al., "Temporal changes in the composition and biomass of beached pelagic Sargassum species in the Mexican Caribbean",

[31] M Hanisak and M Samuel, "Growth rates in culture of several species of Sargassum from Florida, USA", *Hydrobiologia* 151, https://link.springer.com/article/10.1007/BF00046159

[32] Robert Marsh, Hazel Oxenford, Shelly-Ann Cox, Donald Johnson, and Joshua Bellamy, "Forecasting seasonal sargassum events across the tropical Atlantic: overview and challenges", *Frontiers in Marine Science* 9:914501 (2022), https://www.frontiersin.org/articles/10.3389/fmars.2022.914501/full

[33] Godinez-Ortega et al, "A natural history of floating Sargassum species (Sargasso) from Mexico", 19.

[34] Ibid, 19.

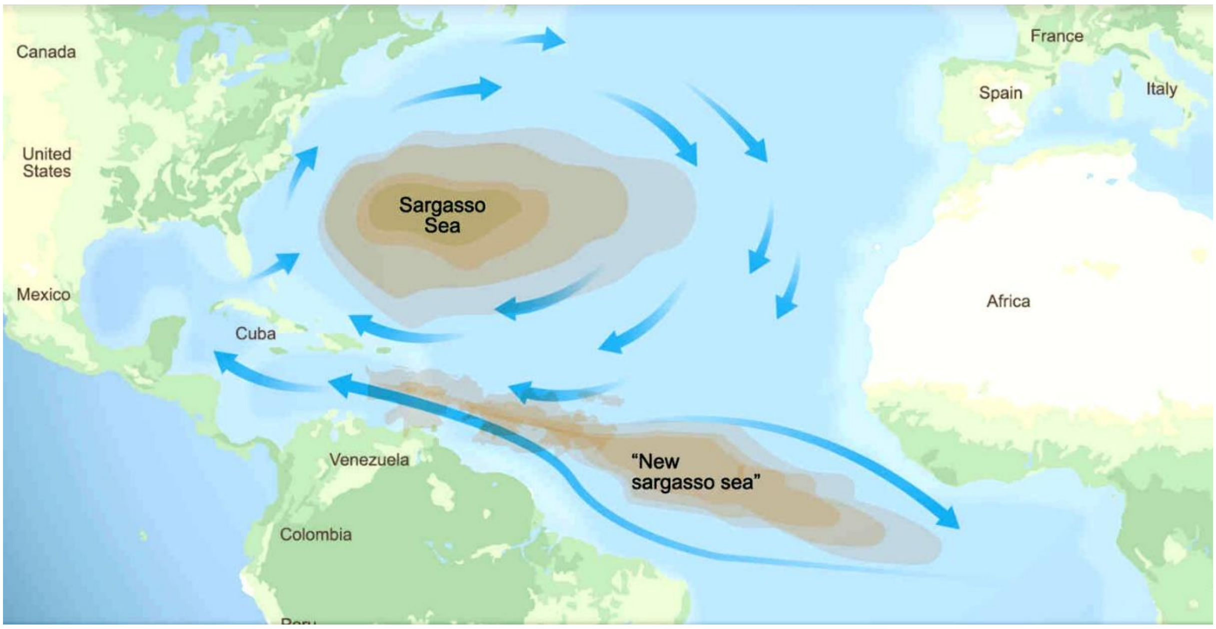
[35] Mengqiu Wang, Chuanmin Hu, Brian Barnes, Gary Mitchum, Brian Lapointe, and Joseph Montoya, "The great Atlantic Sargassum Belt", *Science* 365:6448, (July 2019), https://www.science.org/doi/10.1126/science.aaw7912, 84.

[36] United Nations Environment Programme – Caribbean Environment Program, "Sargassum White Paper: Turning the Crisis into an opportunity", 8.

[37] Wang et al, "The great Atlantic Sargassum Belt", 84.

[38] For more information about the long-distance dispersal of Sargassum from the North Atlantic, please refer to Elizabeth Johns, Rick Lumpkin, Nathan Putman, and Ryan Smith, "The establishment of a pelagic Sargassum population in the tropical Atlantic: Biological consequences of a basin-scale long distance dispersal event", *Progress in Oceanography* 182:102269, (January 2020), https://www.researchgate.net/publication/338634725_The_establishment_of_a_pelagic_Sargassum_population_in_the_tropical_Atlantic_Biological_consequences_of_a_basin-scale_long_distance_dispersal_event

Figure 2.3: The Great Atlantic Sargasso Belt[39]



Studies focusing on the life cycle of sargassum have found that the bloom peaks in the middle of the year and that it appears to develop largely from small populations of the seaweed in the central Atlantic, with some contribution from West Africa. 19 years of recorded of satellite observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) enabled to study the various in Sargassum biomass.[40] In 2018, the GASB stretched for 8850 km, covered 6000 km^2 with an estimated 20 million tonnes of algal mass.[41] According to the data from the University of Florida's Optical Oceanography Laboratory, the record was broken again in June 2022 when more than 24 million tonnes of sargassum were detected in the entire Atlantic area. This is 20% higher than the previous record observed in June 2018.[42]

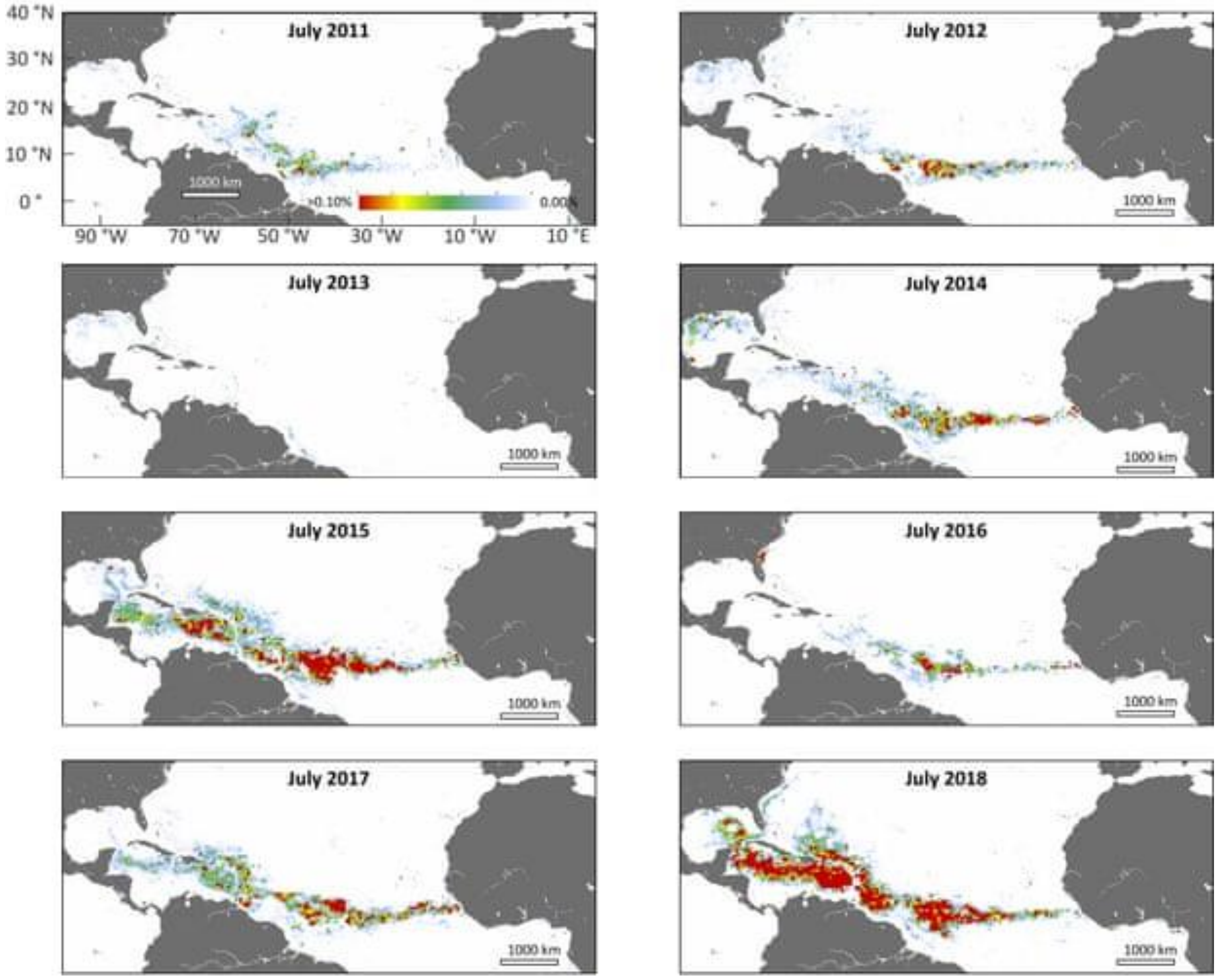
[39] Image taken from Cleaner Oceans Foundation, "New Sargasso Seas", accessed 2 December 2022, https://www.blue-growth.org/Oceans_Rivers_Seas/Sargasso_New_Seas_Atlantic_Indian_Pacific_Oceans_Migration_Seaweed_Blooms_World_Plagues.htm

[40] Wang et al, "The great Atlantic Sargassum Belt", 83.

[41] Ibid, 83.

[42] University of South Florida, Optical Oceanography Laboratory, "Satellite-based Sargassum Watch System SaWS", accessed 2 December 2022, https://optics.marine.usf.edu/projects/saws.html

Figure 2.4: Density of Sargassum blooms in the Atlantic Ocean between 2011 and 2018

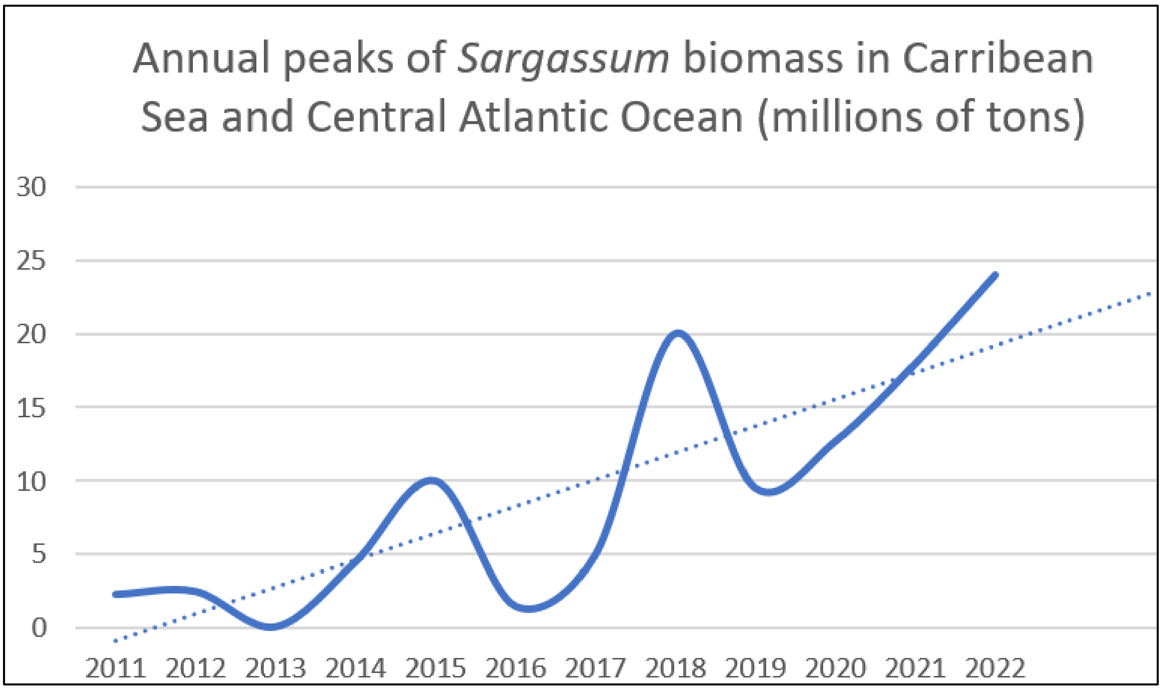


Source: University of South Florida, Optical Oceanography Laboratory

The algal masses in the GASB show large interannual variability, which to date has been difficult to predict. Nevertheless, the influx of sargasso into the Caribbean shows a seasonal pattern, as the North Equatorial Counter Current breaks down from January until May – the generated westward surface flow transports sargasso into the Caribbean. Various tools and methods have been developed to attempt and predict the drift of Sargassum throughout the region.[43]

[43] For more details about these different methods, please read Marsh et al, "Forecasting seasonal Sargassum events across the tropical Atlantic: overview and challenges"

Figure 2.5: Annual peaks of Sargassum biomass in the Atlantic Ocean (million tonnes)



Source: University of South Florida, Optical Oceanography Laboratory

2.3.2 Causes

There is general agreement that this **phenomenon is the result** of a combination of biophysical and climatic factors of anthropogenic origin which encouraged an extraordinary proliferation of the seaweed in a new source region across the Equatorial Atlantic. Some of the causes behind the Sargassum blooms which have been occurring since 2011 include[44]:

- increased nutrient discharges of large rivers (Amazon, Orinoco, Congo) due to deforestation and other upstream activities[45]
- stronger upwelling off the coast of Northwest Africa;
- changes in the amount or deposition patterns of Sahara dust containing iron and nutrients;
- changes in the mixed layer depth resulting in higher replenishment of near-surface nutrient stocks;
- higher sea surface temperatures and associated storm intensity;

[44] For more information please refer to A Lopez-Contreras, M van der Geest, B Deetman, S van den Burg, G Burst, and G Vrije, "Opportunities for the valorisation of pelagic Sargassum in the Dutch Caribbean", *Wageningen University and Research* Report 2137 (March 2021), https://edepot.wur.nl/543797 and Y Fidai, J Dash, E Thompkins, T Tonon, "A systematic review of floating and beach landing records of Sargassum beyond the Sargasso Sea", *Environmnetal Research Communications* 2 (2020), https://iopscience.iop.org/article/10.1088/2515-7620/abd109/pdf

[45] Although studies suggest that riverine fertilisation is unlikely controlling factor for both seasonal and interannual variability of the *Sargassum* biomass. For more information on this, please refer to Julien Jouanno, Jean-Sebastien Moquet, Leo Berline, Marie-Hélène Radenac, William Santini, Thomas Changeux, Thierry Thibault, Witold Podlejski, Frederick Ménard, Jean-Michel Martinez, Olivier Aumont, Julio Scheinbaum, Naziano Filizola, and Guy N'Kaya, "Evolution of riverine nutrient export to the tropical Atlantic over the last 15 years: is there a link with Sargassum proliferation?", *Environmental Research Letters* 16 (2021), https://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers21-03/010081035.pdf

- Sargassum population reached a "tipping point" in 2011 forced by an extreme negative phase of the North Atlantic Oscillation and that vertical mixing dynamics below the Intertropical Convergence Zone (ITCZ) sustain Sargassum growth in the Central Tropical Atlantic (in line with chlorophyll concentrations observed in ITCZ).[46] This echoes Skliris et al who suggests that "changes in the intensity of sargassum blooms one year to the other are mainly driven by anomaly patterns of regional winds and currents controlling nutrient abundance and concentrating / dispersing or transporting sargassum biomass, rather than changes in surface warming, light, or river outflows."[47]

2.3.3 Sargassum as a key ecosystem resource

Sargassum plays a significant role in the marine ecosystem. Mats of *S natans* and *S fluitans* in particular have been called the "golden floating rainforest of the Atlantic Ocean" as they provide essential biodiversity habitats and serve as hotspots for biodiversity and productivity in otherwise substrate poor, low-nutrient open-ocean waters.[48]

As the Sargassum drifts round it collects "passengers" which contribute to the biodiversity which varies seasonally.[49] The complex trophic network of energy flows among herbivores, predators, and detritivore includes over 145 species of marine invertebrates, 111 species of fish (white marlin, tuna, bill fish, mahi-mahi, porbeagle shark, dolphinfish and eels)[50], 26 species of seabird, and 4 species of sea turtles (loggerhead, hawksbill, Kemp's ridley and green) that use the rafts as a refuge to reduce predation risk during early life stage.[51] Ten species endemic to the environment are camouflaged to match the surroundings, including the sargassum fish which has even has modified fins that allow it to crawl through the seaweed.[52] Like an oasis in the desert, the particulate rains from Sargassum mats also nourish all levels of the ocean's food chain, at all depths. It contributes to around 60% of the total primary production in the upper 1-metre column of water.[53] Once it loses buoyancy after about a year, the Sargassum sinks to the seafloor and provides energy to ocean life.[54] There is increasing evidence that certain deep-sea fish and invertebrates consume the remains of the algae fallen to the bottom,

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[46] Jouanno et al, "Evolution of riverine nutrient export to the tropical Atlantic over the last 15 years: is there a link with Sargassum proliferation?", 2.

[47] Nikolaos Skliris, Robert Marsh, Kwasi Addo, and Hazel Oxenford, "Physical drivers of pelagic sargassum bloom interannual variability in the Central West Atlantic over 2010 – 2020", *Ocean Dynamics* 72:21 (May 2022), https://link.springer.com/article/10.1007/s10236-022-01511-1,

[48] Dan Laffoley, Howard Roe, MV Angel, Jeff Ardron, Nicholas Bates, LL Boyd, Sandra Brooke, Kristen Buck, Craig Carlson, B Causey, MH Conte, Sabine Christiansen, Jesse Cleary, J Donnelly, SA Earle, R Edwards, Kristina Gjerde, SJ Giovanni, S Gulick, M Gollock, J Hallet, Patrick Halpin, Reinhold Hanel, Arlo Hemphill, Rodney Johnson, Anthony Knap, Michael Lomas, Sheila McKenna, Michael Miller, Petter Miller, FW Wing, Russell Moffitt, Norman Nelson, Lindsay Parson, AJ Peters, Joanna Pitt, Philippe Rouja, J Roberts, DA Siegels, Amy Siuda, DK Steinberg, A Stevenson, Rashid Sumalia, W Swartz, Tammy Warren, and V Vats, "The protection and management of the Sargasso Sea: The golden floating rainforest of the Atlantic Ocean. Summary Science and Supporting Evidence Case", *Sargasso Sea Alliance*, (January 2011), http://www.sargassoseacommission.org/storage/documents/Sargasso.Report.9.12.pdf

[49] Laffoley et al, "The protection and management of the Sargasso Sea: The golden floating rainforest of the Atlantic Ocean. Summary Science and Supporting Evidence Case", 13.

[50] Melissa Gaskill, "Significant Sargassum", *Divers Alert Network*, (May 2013), https://dan.org/alert-diver/article/significant-sargassum/

[51] The Ocean Foundation, "Sargassum Factsheet"

[52] The species include: the Sargassum crab (*Planes minutes*), Sargassum shrimp (*Latreutes fucorum*), Sargassum pipefish (*Syngnathus pelagicus*), Sargassum anemone (*Anemonia sargassensis*), the Sargassum slug (*Scyllea pelagica*), the Sargassum snail (*Litiopa melanostoma*), the amphipods *Sunampithoe pelagica* and *Biancolina brassicacephala*, and the platyhelminth *Hoploplana grubei*. Most of the endemics are camouflaged in some way and perhaps the most iconic is the Sargassum Angler Fish (*Histrio histrio*), in Laffoley et al, "The protection and management of the Sargasso Sea: The golden floating rainforest of the Atlantic Ocean. Summary Science and Supporting Evidence Case", 13.

[53] The Ocean Foundation, "Sargassum Factsheet"

[54] Ibid

thereby contributing to the maintenance of deep-sea communities.[55] Even small quantities of beached sargassum have positive environmental effects. By providing food for various coastal species such as amphipods and the subsequent food chain. They also prevent erosion by absorbing wave energy and depositing sediments and nutrients onto beaches.[56] Sargassum collects wind-blown sand during its drift and when it washes back ashore, restores beaches and acts as a short-term anti-wind erosion.[57]

2.3.4 The negative externalities of Sargassum influxes

Although pelagic Sargassum is recognised as an important biological resource for marine conservation and evolution, the overgrowth of floating biomass and inundation along the coasts have caused negative environmental and socio-economic effects. As the United Nations' Environment Programme - Caribbean Environment Programme report explains, "the types and severity of impacts and feasibility of responses all vary spatially across the Caribbean according to several factors, including: coastline position (level of exposure to sargassum influxes), geomorphology and coastal dynamics of the impacted coastline, and presence/absence/proximity of vulnerable resources, activities and operations along the impacted coastline."[58] The impacts of holopelagic blooms in the Atlantic region can be divided into two main categories: environmental and socio-economic.

Excessive sargassum impacts to the environment are:

- Blocking light and changing the structure of benthic communities[59] ;
- Creating natural deadzones due to the decomposition of biomass;
- Killing of mangrove and seagrasss seedlings by becoming trapped in mangrove forests. It decomposes and creates anoxic conditions with changes to the biochemistry and hydrodynamics of the mangrove root system[60] ;
- Eutrophication, reduction in light, oxygen, and pH in near-shore waters, increase in turbidity nutrient loading (high levels of nitrates and phosphates), bacterial loading, and presence of toxins (e.g., high ammonium and hydrogen sulphide concentrations, and heavy metals.[61] Dense stands of *S. muticum* also contribute to reducing light, dampening flow, and increasing competition for nutrients with other seaweeds [62];

[55] Aharon Fleury and Jeffrey Drazen, "Abyssal scavenging communities attracted to Sargassum and fish in the Sargasso Sea", *Deep Sea Research Part 1: Oceanographic Research Papers*, 72 (February 2013), 141-147, https://www.sciencedirect.com/science/article/pii/S0967063712002245

[56] The Ocean Foundation, "Sargassum Factsheet"

[57] Rachel Innocenti, Rusty Feagin, and Thomas Huff, "The role of Sargassum macroalgal work in reducing coastal erosion", *Estuarine Coastal and Shelf Science* 214 (September 2018), 10.1016/j.ecss.2018.09.021

[58] United Nations Environment Programme – Caribbean Environment Program, "Sargassum White Paper: Turning the Crisis into an opportunity", 11.

[59] Peter Schumann, Jeanelle Irvine, Hazel Oxenford, Karima Degia, and Julian Valderrama, "The potential economic impacts of sargassum inundations in the Caribbean", SargAdapt Project Report (January 2022), https://www.iweco.org/sites/default/files/2022-02/IWEco_Project_C2_FinalReport_The_potential_economic_impacts_of_sargassum_inundations_in_the_Caribbean_Part1_Insights_from_the_literature_Feb2022.pdf, 19.

[60] Schumann et al, "The potential economic impacts of sargassum inundations in the Caribbean", 20.

[61] Ibid, 17.

[62] Kevin Britton-Simmons, "Direct and indirect effects of the introduced alga Sargassum muticum on benthic, subtidal communities of Washington state, USA", *Marine Ecology Progress Series* 277 (August 2004), https://www.int-res.com/articles/meps2004/277/m277p061.pdf, 2.

- Risk of environmental contamination by heavy metals. The Caribbean population faces the consequences of long-term exposure to arsenic from bivalves and other seafoods[63] ;
- Changes in the behaviour of nesting (sea turtles) lethal consequences for air breathing species unable to surface for air;
- Sargassum clean-up's unintended removal of sand (resulting in substantial beach erosion and destruction nests)[64];
- Sargassum mitigation measures (nets) trap hatchlings and other mammals;
- Increase in the chemical and biochemical oxygen demand, anoxia alters the quality of the sand, affects coastal ecosystems, and generates greenhouse gases (GHG).[65]

The socio-economic impacts of sargassum blooms are:

- Increased erosion of beaches reduces coastal protection and reinforces the vulnerability of coastal communities to extreme weather events;
- Release of toxic gases that pose fatal health problems for humans. In Martinique and Guadeloupe in 2018, more than 11 000 residents were diagnosed with acute exposure to H_2S gas produced by decaying Sargassum. Sargassum is also described as a "health issue" by France's regional health agencies[66];
- Costs associated with cleaning up the excessive biomass. The Mexican government spent approximately US $ 17 million to remove over 500,000 tonnes of seaweed from coastal areas in 2018, and an additional US $ 2.6 million to remove 85,000 tonnes in 2019.[67] The cost of cleaning beaches on the Mexican Gulf of Mexico is around US$ 5 million and the estimated cost to remove the Sargassum across the Caribbean is US$ 120 million.[68]
- Threat to tourism, due to the unpleasant odour and excessive stranding biomass. The Caribbean region is highly dependent on tourism which provides over 15% of GDP and 14% of jobs, with a tourist spend of US$ 31.4 billion in 2016.[69]
- The release of hydrogen sulphide (H2S) gas also causes the corrosion of copper cables, electronic equipment and domestic appliances in nearshore dwellings;
- Excessive Sargassum also threatens extractive blue economy activities. Impacts commonly reported by fishers include obstructed access to landing sites, increased time spent at sea to

[63] Damien Devault, Emma Modestin, Victoire Cottereau, Fabien Vedie, Valérie Stiger-Pouvreau, Ronan Pierre, Alexandra Coynel, and Franck Dolique, "The silent spring of Sargassum", *Environmental Science and Pollution Research* 28 (January 2021), https://link.springer.com/article/10.1007/s11356-020-12216-7

[64] United Nations Environment Programme – Caribbean Environment Program, "Sargassum White Paper: Turning the Crisis into an opportunity",12.

[65] José Sosa Olivier, José Laines Canepa, David Zarate, Anabel Diaz, Donato Jaramillo, Heidi Garcia, Berenice Lopez, "Bioenergetic valorization of Sargassum fluitans in the Mexican Caribbean: the determination of the calorific value and washing mechanism", *AIMS Energy* 10:1, (January 2022), https://www.aimspress.com/aimspress-data/aimse/2022/1/PDF/energy-10-01-003.pdf

[66] For more information about the health related issues, read Agence Nationale de Sécurité Sanitaire, alimentation, environnement, travail, "Exposition aux émanations d'algues sargasses en décomposition aux Antilles et en Guyane", (March 2017), https://www.anses.fr/en/system/files/AIR2015SA0225Ra.pdf

[67] Schuhmann et al, "The potential economic impacts of sargassum inundations in the Caribbean", 30.

[68] Vicky Karantzavelou, "Sargassum clean-up costs Caribbean US$120 million", *Travel Daily News* (29 July 2019), https://www.traveldailynews.com/post/sargassum-clean-up-costs-caribbean-us120-million

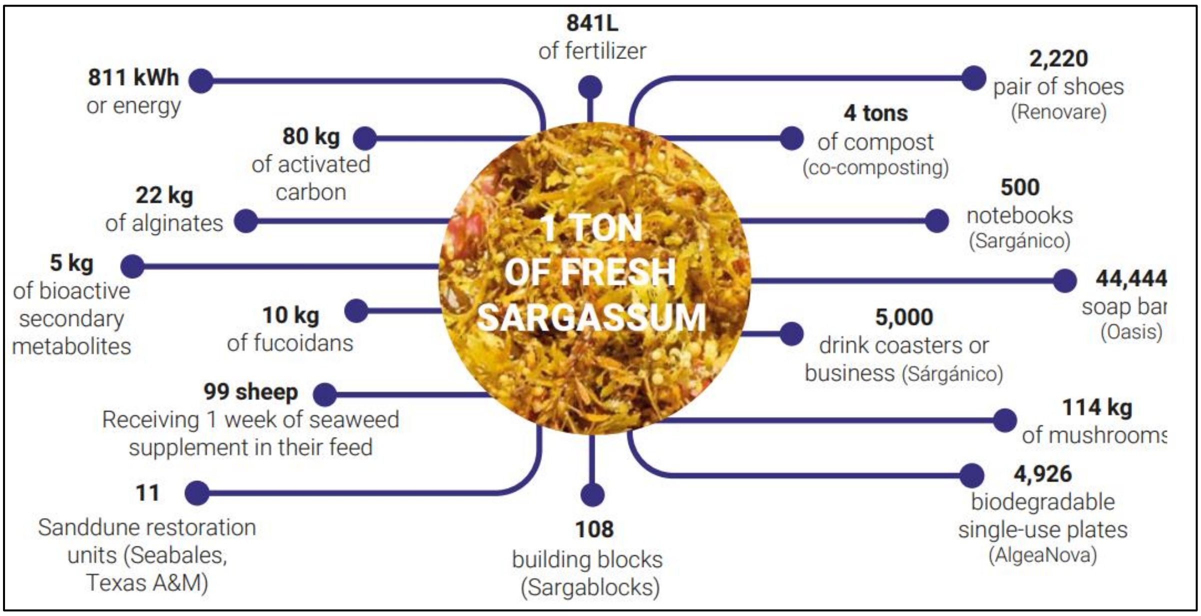
[69] Johns Milledge, Supattra Maneein, Elena Arribas Lopez, Debbie Barlett, "Sargassum inundations in Turks and Caicos: methane potential and proximate, ultimate, lipid, amino acid, metal and metalloid analyses", *Energies* 13:6 (2020), https://www.mdpi.com/1996-1073/13/6/1523

manoeuvre around seaweed mats, clogged fishing gear (traps and nets) as well as damage to fishing equipment and vessels due to entanglement. Local artisanal fisheries play a significant role in the livelihoods and food security of more than two million people in the region. In Barbados, the arrival of massive amounts of Sargassum have coincided with a dramatic decrease of 72% in one of the island's most important fisheries.[70] Algal blooms have also had similar impacts in other parts of the world. An economic loss of about US$ 73 million was estimated due to damaged seaweed aquaculture in the Jiangsu Shoal, China. [71] Declining fishing catches due to Sargassum have also been reported in West Africa, threatening the livelihoods of coastal communities.

2.4 Main applications

The surge in Sargassum blooms across the Atlantic region has caused funds to be raised for businesses and projects that mitigate the effects and costs for coastal economies and find ways to derive benefits from these strandings. Yet the use of Sargassum around the world is limited to certain niche areas, and there is no real market for the time being. In the Caribbean especially, the use of seaweeds has traditionally been quite limited. While efforts to explore the potential opportunity are underway, the reality is that sargassum influxes remain more of a hazard than a benefit. The exact chemical composition and nutrient value of Sargassum, essential for identifying applications, is likely to vary based on the species, the location, the time of the year and environmental conditions. [72] Desrochers et al.'s study calculated the relative product yields that could be produced from 1 tonne of fresh sargassum.[73]

Figure 2.6: Product yields from 1 tonne of fresh sargassum



Source: Desrochers et al, "Sargassum Uses Guide: a resource of Caribbean researchers, entrepreneurs, and policy makers"

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[70] Ryan Schuessler, "The Eastern Caribbean is swamped by a surge of seaweed", *Hakai Magazine* (June 2018), https://hakaimagazine.com/news/the-eastern-caribbean-is-swamped-by-a-surge-of-seaweed/

[71] Qianguo Xing, Ruihong Guo, Lingling Wu, Deyu An, Ming Cong, Song Qin, Xuerong Li, "High resolution satellite observations of a new hazard of golden tides caused by floating sargassum in winter on the Yellow Sea", *IEEE Geoscience and Remote Sensing Letters* 99, 10.1109/LGRS.2017.2737079

[72] Desrochers et al, "Sargassum Uses Guide: a resource of Caribbean researchers, entrepreneurs, and policy makers", 16.

[73] Ibid, 84.

2.4.1 Feed

Various studies covered the inclusion of Sargassum in animal nutrition, covering both animal performance and immunity aspects as well as product quality. Examples of benefits reported in the literature for the use of Sargassum species include improved meat quality, improved milk quality and yield (fat levels and iodine content), improved digestibility and gut health, increased stress tolerance, and improved immune system functions.

Research projects using holopelagic Sargassum:

- Amadéite Groupe (Guadeloupe): how to use Sargassum for animal, plant, and human health.
- Instituto Nacional de Ciencas Medicas y Nutricion Salvador Zubiran (Mexico): use of natural ingredients, including Sargassum, for chicken and small ruminants feed supplements.
- PYROSAR project (Guadeloupe): valorisation of Sargassum by pyrolysis and application for food safety.
- SARGWA Consortium (Guadeloupe): Sargassum applications in animal feed.

Commercial projects using holopelagic Sargassum:

- Awganic Inputs (Jamaica): Sargassum-based goat feed.

Nevertheless, it should be noted that longer-term studies might be required to evaluate the potential impact of contaminants, and in particular arsenic, which was not usually quantified in the seaweed meals.[74]

2.4.2 Food

Only *S. fusiforme*, also known as Hizikia fusiforme, is currently used for human consumption. Other Sargassum species, including *S. fluitans* and *S. natans*, are described as being consumed in the Caribbean but their peculiar taste and bitterness are mentioned.[75] They are consumed fresh or rehydrated, fried, possibly after boiling or even as flour in tortillas.

Research projects using holopelagic Sargassum:

- Texas A&M University (USA): In 2015, students and researchers, in collaboration with Galveston Island Brewery, made and tested a sargassum craft beer
- University of the West Indies (Barbados, Jamaica and Trinidad & Tobago): alginate extracts for different uses

Commercial projects using holopelagic Sargassum:

- Alquimar & Grupo Metco (Mexico): alginate extracts
- Mixologist Bruno Lardelli (Mexico): cocktail drink ‘pineapple gift’ using
- Tomfoodery Kitchen (Cayman Islands): Chef Thomas Tennant has been experimenting with sargassum as an ingredient in different dishes

Yet the direct consumption of pelagic sargassum is not advisable, since there is evidence that it can contain high levels of arsenic and other components which may be toxic. Traditional processes of

[74] Desrochers et al, “Sargassum Uses Guide: a resource of Caribbean researchers, entrepreneurs, and policy makers”, 29.

[75] Damien Devault, Ronan Pierre, Helene Marfaing, Franck Dolique, and Pascal Jean Lopez, “Sargassum contamination and consequences for downstream uses: a review”, *Journal of Applied Phycology* 33 (November 2021), https://link.springer.com/article/10.1007/s10811-020-02250-w , 15.

soaking and boiling applied to *S. fusiforme* significantly reduce their arsenic content, but they are still above regulatory levels.[76] Both collection of benthic and holopelagic Sargassum raise numerous quality concerns: uncertain quality and food safety, lack of traceability, unknown history of growth and potential contaminations and so on.

2.4.3 Biostimulants

The use of seaweed as "metabolic enhancers" has increasingly been investigated to reduce the use of fertilisers while still bolstering crop production and improving the soil's properties and fertility. Although biostimulants are often used as a foliar-application (spraying directly onto leaves), they are also applied directly onto the soil or introduced into an irrigation system.

Research projects using holopelagic Sargassum:

- Amadéite Group: 6-month project to calibrate sargassum treatment process and optimisation of extract of compounds.
- Centro de Investigación Científica de Yucatán (Mexico): sargassum as growth substrate for mushroom cultivation
- ECO3SAR project (France & Guadeloupe): valorisation of sargassum, with a focus on composting.
- INRA-Université des Antilles (Guadeloupe): sargassum analysis of pollutants, composting and direct spreading.
- Institut Technique Tropical - IT2 (Martinique): agronomic and toxicological analyses of effects resulting from application of pelagic sargassum compost and direct field spreading.[77]
- SARGOOD project (Guadeloupe & collaborators): holistic approach to sargassum valorisation including developing bioelicitors, biostimulants and other agricultural products.
- SAVE project (France & Martinique): sargassum agricultural valorisation including digestates.

Commercial projects using holopelagic Sargassum:

- Algas Organics (St. Lucia): sargassum-based plant-tonics.
- AlgeaNova (Dominican Republic): using sargassum for co-composting with other organic wastes and are also producing 100% sargassum mulch.
- Alquimar (Mexico): commercialising a biofertiliser called Alquifert.
- Beacon Farms (Cayman Islands): Sargassum as a compostable soil additive for use in farming.
- Dianco México (Mexico): developing a sargassum-based fertiliser.
- Holdex (Martinique): using sargassum in co-composting with other organic wastes.
- Red Diamond Compost (Barbados): have been commercialising a sargassum-based biostimulant called Super Seaweed.
- Salgax (Mexico): are commercialising a range of sargassum-based.

[76] Ibid, 15.

[77] United Nations Environment Programme – Caribbean Environment Program, "Sargassum White Paper: Turning the Crisis into an opportunity", 16.

As with the food and feed applications, it is important to recall that high salt and arsenic contents present in Sargassum can also damage soils over the long-term and potentially be passed up the food chain through food crops.

2.4.4 Biomaterials

Seaweeds across the world are already being used to produce composite materials. Holopelagic applications are multiplying and have the advantage of not competing for land space used for food production.

Paper

Seaweed is considered as a good ingredient for use in papermaking due to the presence of significant amounts of cellulose and negligible lignin content in their cell walls. Alginate extracts are used to reinforce the water resistance and smoothness of the paper surface.

Commercial projects using holopelagic Sargassum:

- Golden Tide project, Wouter Osterholt (Curaçao): 100% sargassum-based artisanal paper.
- Sargánico (Mexico): producing high quality notebooks, folders, etc from Sargassum.
- Sargasse Project (St. Barths): Making 100% sargassum-based paper and cardboard products.
- Sargazbox (Mexico): Developing cardboard boxes with sargassum cellulose.
- The Marine Box (Martinique): Developing various paper and cardboard products made with sargassum.

Clothing

Seaweeds can be used to produce eco-friendly fibres, foams, dyes and coatings for the fashion industry and are increasingly being used for sportswear and accessories. The textile printing industry also uses sodium alginate for thickening and enhancing dyes. The only known use of pelagic sargassum is Renovare (Mexico), which has developed an eco-friendly shoe using recycled plastic, biodegradable resins and sargassum seaweed.

Construction materials

Seaweeds are being used in the production of composite material for use in a variety of construction material.

Research projects using holopelagic Sargassum:

- SarGood project (Guadeloupe): research on innovative eco-materials and panels.

Commercial projects using holopelagic Sargassum:

- Biogen (Barbados): The company has carried out trials to make a sargassum-based resin board for industrial development.
- Sargablock (Mexico): sargassum-based construction blocks to build housing for low-income families.
- The Marine Box (Martinique): add sargassum to bioasphalt for use in paving roads.

Bioplastics and biopolymers

Several recent studies are investigating the exploitation of Sargassum's polysaccharide composition. They can either be used as feedstock for fermentation by microorganisms to produce lactic acid or for extraction of polysaccharides (alginates), both of which are used in the manufacture of bioplastics.

Research projects using holopelagic Sargassum:

- Clemson University & Rochester Institute of Technology (USA): nanocomposite films with Sargassum.
- NOVUNDI Environnement & AlgoPack (France & Guadeloupe): feasibility of producing sargassum based bioplastics.
- University of the West Indies (Barbados & Trinidad): sargassum for use in the manufacture of bioplastic.

Commercial projects using holopelagic Sargassum:

- Abaplas (Mexico): testing production of a bioplastic made of 30% sargassum and 70% plastic for use in different applications, including ecological housing.
- AlgeaNova/EnergyAlgae (Dominican Republic): single use plates made with 50% sargassum and 50% cassava.
- EnerGryn (Mexico): testing production of two types of bioplastics: biodegradable pellets and recyclable bioplastic for use in making water heaters, cups and plates.
- Le Floch Depollution (France): testing development of two different types of bioplastics made with 30% sargassum and 70% thermoplastic resins as well as 40% sargassum and 60% polylactic acid.

2.4.5 Cosmetics

Seaweed extracts are widely used in the world of cosmetics, especially alginates and bioactive compounds, the latter imparting many beneficial properties for skin and hair care. Sargassum also demonstrated various applications in these domains, with numerous publications having described the in vitro anti-oxidant and whitening properties of Sargassum.[78]

Research projects using holopelagic Sargassum:

- Nexo project, Tecnológico de Monterrey (Mexico): extracting alginates and fucoidans from the cell walls of sargassum to determine potential uses in bath gels, creams and other cosmetics.
- University of the West Indies (Barbados, Jamaica, Trinidad & Tobago): alginate extract from pelagic sargassum for use in cosmetics and other products.

Commercial projects using holopelagic Sargassum:

- Alquimar & Grupo Metco (Mexico): Extracting alginate from pelagic sargassum for use in several sectors including cosmetics.
- Oasis Laboratory (Barbados): Producing a sargassum skincare line, including bath bars.
- Salgax (Mexico): Looking to commercialise a sargassum hair treatment.

Yet it may be difficult to address cosmetic manufacturer's needs with holopelagic Sargassum. This is particularly true as a large number of benthic Sargassum species are available globally, with harvestable stocks largely sufficient for the small volumes required for cosmetic extracts, and some of these species. Moreover, the small volumes required would not have any significant impact on the volumes to be handled.

[78] Devault et al, "Sargassum contamination and consequences for downstream uses: a review", 14.

2.4.6 Health products

The crude extract of the Chinese brown seaweed *Sargassum* has been used to treat fever, infections, laryngitis and other ailments by the local population while species of *Kappaphycus* and *Eucheuma* genera are used in Vietnamese medicine to reduce the occurrence of tumors, ulcers and headaches.[79] Many studies have confirmed the potential of Sargassum due to their anti-oxidant and antimicrobial, anti-tumour, anti-inflammatory, anti-coagulant and anti-thrombotic, and anti-viral properties.[80]

Research projects using holopelagic Sargassum:

- Nexo project, Tecnológico de Monterrey (Mexico): extracting alginates and fucoidans from the cell walls of sargassum to determine potential uses.
- SARSCREEN project (Guadeloupe): to determine pharmacological potentials of sargassum extracts against non-communicable diseases common and widespread across the Caribbean.

Commercial projects using holopelagic Sargassum:

- Alquimar & Grupo Metco (Mexico): both companies have been working on alginate extracts for use in several sectors, with Alquimar commercialising fucoidans nationally.

To date there has been limited research on pelagic sargassum and the potential health-related applications. As with other applications, the therapeutic effectiveness and safety of pelagic sargassum extracts remain unknown and should therefore be treated with caution until properly tested.

2.4.7 Energy

Use of algae to produce bioenergy is promising due to their fast growth and high yield, low lignin content and ability to capture CO_2. Sargassum can be used to produce energy via anaerobic digestion. Moreover, since Sargassum grows at sea, their production does not compete with agriculture (food production) for arable land. So far, the most feasible applications of Sargassum for the production of energy are twofold.

Bioethanol

The use of micro-organisms to produce bioethanol through the fermentation of Sargassum has been proven, but the commercialisation remains difficult "due to the high cost of pre-treatment needed to make the seaweed suitable for fermentation, and the need to identify suitable salt-tolerant microorganisms."[81]

Biomethane

Studies indicate that methane yields achieved with holopelagic Sargassum only reach 17 to 37% of the theoretical yields (due to the complexity of the polysaccharides, the salinity, sulfur, and polyphenols, and the low carbon to nitrogen ratio). [82] They need to be mixed with other types of biomass such as food waste and agricultural by-products (in a process known as co-digestion) to increase the methane yield.

[79] Silvia Lomartire and Ana Gonçalves, "An overview of potential seaweed-derived bioactive compounds for pharmaceutical applications", *Marine Drugs* 20:2 (February 2022), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8875101/

[80] For more information, please refer to reference in Devault et al, "Sargassum contamination and consequences for downstream uses: a review", 20.

[81] Desrochers et al, "Sargassum Uses Guide: a resource of Caribbean researchers, entrepreneurs, and policy makers", 41.

[82] Valeria Chavez, Abigail Uribe-Martinez, Eduardo Cuevas, Rosa Rodriguez Martinez, Brigitta van Tussenbroek, Vanessa Fancisco, Miriam Estevez, Lourdes Celis, Veronica Monroy Velazquez, Rosa Leal-Bautista, Lorenzo Alvarez Filip, Marta Garcia Sanchez, Luis Masia, and Rodolfo Silva, "Massive influx of pelagic Sargasum spp. on the coasts of the Mexican Caribbean 2014- 2020: challenges and opportunities", *Water* 12:10 (2010), https://www.mdpi.com/2073-4441/12/10/2908

Research projects using holopelagic Sargassum:

- Centro de Investigación Científica de Yucatán (CICY) (Mexico): prototype methodology that involves mixing sargassum with a locally sourced fungus, able to degrade lignin, and a bacterial inoculum to produce methane.
- Ecodec (Guadeloupe): pilot trial to evaluate sargassum's potential as a fuel to power a biomass boiler.
- Innovation Développement (Guadeloupe): pilot sargassum methanisation trial.
- SAVE (France/Guadeloupe/Martinique): Study on anaerobic digestion of sargassum and factors affecting methane production.
- University of the West Indies (Barbados & Trinidad).

Commercial projects using holopelagic Sargassum:

- Biogen (Barbados): This company is investigating anaerobic co-digestion of sargassum.
- Damen / Maris Group (Netherlands): Sargassum in biofuel applications.
- Energryn (Mexico): Use of sargassum blended with other organic wastes to produce biopellets for use in local hotels.
- EnergyAlgae (Israel & Dominican Republic): Use of sargassum in anaerobic biogas co-digestion units.
- Mécaméto (France): Sargassum as feedstock in the patented dry methanisation mobile technology Hemer.
- Num SMO Technologies (Guadeloupe): pyrolysis of sargassum to produce electricity and activated carbon.
- The Pelikan System (St. Barts): 'autocombustore' system fed with biosargassum pellets to generate electricity through an electric turbine generator.

2.4.8 Ecosystem services

Sargassum provides natural ecosystem services and several projects are looking to make use of it to restore coastal dunes, through stabilising sand dunes and fertilising dune vegetation. Holopelagic Sargassum has also been reported to capture carbon dioxide through photosynthesis and plant growth. Some projects are looking into sinking Sargassum to the deep ocean floor to potentially sequestering carbon.

Resesarch projects using holopelagic Sargassum:

- Moon Palace Resort (Mexico): They have been using sargassum-based compost to enhance coastal vegetation growth to reduce erosion and protect their beach and hotel structures.
- SOScarbon (Dominican Republic): Developing technology to sink pelagic sargassum and potentially sequester blue carbon in the deep ocean.
- Texas A&M University (USA): using sargassum bales to protect dunes from erosion and promote plant growth.
- WIRRED (Barbados): Using sargassum to help regenerate dune vegetation.

These projects are nonetheless limited in their scope, or, in the case of carbon offsetting, hampered by important knowledge gaps. Main challenges for commercialising blue carbon credits include:

- The list of negative environmental and socio-economic externalities (see § 2.3.4 above)
- the ownership of Sargassum;
- the loss of biodiversity and the potential creation of deep-sea dead zones due to excessive accumulation of biomass in oxygen minimum zones of the ocean.[83]

2.4.9 Bioremediation

Considered as low-cost and environmentally friendly bio absorbents, Sargassum species throughout the world have excellent biosorption properties, capable of removing a variety of contaminants (high nutrient loads, heavy metals, dyes, phenols) from water.[84] Holopelagic Sargassum is used to produce high quality activated carbon, useful for in filters for purifying air and water, odour control, and the bioremediation of contaminated soils and coastal waters.[85] Sargassum is also efficient in removing organic dyes with removal efficiencies of 95–98%.[86]

Research projects using holopelagic Sargassum:

- Centre for Applied Physics and Advanced Technology (Mexico): sargassum filters for bioremediation, removing contaminants such as metals, sulphates and pigments from water.
- COVACHIM-M2E laboratory (University of Antilles in Guadeloupe & French Guiana): soil remediation, pesticide sequestration in animals and water treatment applications.
- Instituto Tecnológico de Santo Domingo (Dominican Republic): Testing sargassum-based AC for water treatment.
- PYROSAR project (Guadeloupe/Martinique): biochar to adsorb the pesticide chlordecone in contaminated areas to allow for safe food production.
- SARtrib project (Guadeloupe): sargassum nano-carbon and nano-oxide for use in filtering pollution gases.
- University of the West Indies (Trinidad): sargassum polymers to create membranes for use as biofilters in the remediation of heavy metals in wastewaters.

2.5 Challenges and recommendations

Most solutions seeking to valorise Sargassum – wild and beach cast alike – are not commercially mature yet. This paper will conclude by identifying the various roadblocks and suggesting possible solutions. Although knowledge gaps are the main issue preventing Sargassum-industry from scaling up, it is possible to identify five categories of constraints and challenges.[87]

[83] Desrochers et al, "Sargassum Uses Guide: a resource of Caribbean researchers, entrepreneurs, and policy makers", 62.

[84] Ibid, 48.

[85] Ibid, 48.

[86] Amin Zeraatkar, Hossein Ahmadzadeh, Ahmad Talebi, Navid Moheimani, and Mark McHenry, "Potential use of algae for heavy metal bioremediation, a critical review", *Journal of Environmental Management* 181 (October 2016), 10.1016/j.jenvman.2016.06.059

[87] Hazel Oxenford, Shelly-Ann Cox, Brigitta van Tussenbroek, and Anne Desrochers, "Challenges of turning the sargassum crisis into gold: current constraints and implications for the Caribbean", *Phycology* 1:1, (2021), https://www.mdpi.com/2673-9410/1/1/3/htm

2.5.1 Unpredictable supply

- The proportions of the different morphotypes keep changing over time.
- The aggregate volumes of biomass fluctuate every year.
- Quality of the biomass is also highly variable as a result of the age of the algae, its condition, and whether it contains debris (plastics, driftwood, marine organisms).
- Still no consensus about the causes and driving factors behind Sargassum blooms.
- Limited satellite coverage due to cloud-covered Sargassum source regions.
- Uncertainty in global forecasting models (complex and dynamic ocean region).
- High costs of precision observation tools.

Impact:

- Businesses and investors unable to conduct comprehensive cost projections and analysis to assess the economic feasibility and sustainability of proposed ventures.
- Processors may struggle to secure steady stream of raw materials.

Solutions:

- Improving knowledge and prediction of Sargassum flows in the Atlantic (wider satellite coverage, more comprehensive models) to provide a more comprehensive understanding of its distribution.
- Developing easily accessible platforms to make the sightings and predictions of the sargassum influxes at oceanic, regional and local scale available to the public.
- Developing simple harmonised monitoring protocols using remote sensing technology.
- Combining ecological, physiological, biotechnological and socioeconomic approaches to understand how Sargassum respond to environmental changes.

2.5.2 Chemical composition

- Insufficient and non-standard chemical analyses across the region means there is still considerable uncertainty in the chemical composition of sargassum.
- High cost of such procedures and limited testing facilities in the region.
- High variability in reported concentrations of many components, amplified by the type of species as well as spatial and temporal differences.
- Uncertainty of levels of micropollutants after the different processing of sargassum.

Impact:

- Sargassum may not be safe to use in all parts of the value chain.
- Variations in components represent a challenge in certain applications (especially energy and healthcare).

Solutions:

- More extensive sampling and compositional analysis of pelagic sargassum from across the region to improve our understanding of the geographic, seasonal and annual variation in chemical composition.

- Developing protocols to avoid toxins from entering the food chain or causing environmental degradation from widespread applications.
- Improving understanding of how environmental conditions affect the quality and quantity of compounds of interest in *Sargassum* species.
- Engaging in multiple trials using sargassum from different locations and seasons and testing the efficacy of certain sargassum-based products.
- Conducting a mapping of the products that can be derived from different Sargassum species (depending on biomass condition and chemical composition).

2.5.3 Harvesting, storage and transport

- Limited access to, knowledge of, and funds for harvesting and processing of Sargassum.
- Harvesting sargassum is labor-intensive and in many situations requires highly specialised equipment, that many remain idle for months in between influx events.
- Insufficient knowledge for the long-term storage of Sargassum.
- Large infrastructures and specialised equipment are lacking for drying Sargassum.

<u>Impact</u>:

- Sargassum end-products are likely to be more expensive than other market alternatives.
- Acquiring good quality raw material is more costly.
- Scalability of businesses hampered by lack of infrastructure as well as the environmental and human health challenges associated with harvesting and storage.

<u>Solutions:</u>

- Investigating the best storage solutions for sargassum (dried, ground, preserved) to ensure an uninterrupted supply to industry during periods of low or no influxes.
- Identifying the best locations for in-water harvest to avoid biodiversity loss.
- Improving access to knowledge and communication to share lessons learnt and promoting best practices for on-shore and in-water collection methods.

2.5.4 Insufficient funding and support

- Funding to explore valorisation of sargassum has been slow to mobilise and difficult to access.
- Limited capacity and access to collateral among potential entrepreneurs to access funds.
- Insufficient institutional support to accelerate the technology readiness level of research projects.
- Sargassum is generally still viewed as a hazard rather than as a potential opportunity, such that funding has been focused on clean up and mitigation, not on developing beneficial uses.
- A general lack of industrial infrastructure in many countries to support industrial scale uses.

<u>Impact</u>:

- Businesses lack supportive environment to develop and commercialise their products.

Solutions:

- Increasing the number of private-public partnerships for applied research and product development.
- Supporting the capacity of businesses by providing access to funds, marketing, and human resources support.
- Creating the enabling environment for affected stakeholders (fisherfolk and coastal community residents) to pursue sargassum uses as an alternative livelihood.
- Providing incentives for businesses that contribute to governments' cost recovery arrangements for cleaning beaches of sargassum.
- Fostering creativity through innovation hubs, hackathons and pitch competition.
- Encouraging the development of transposable and mobile solutions so that all islands in the region can create local value out of sargassum.

2.5.5 Management and regulation

- Inadequate knowledge sharing mechanisms across countries and sector.
- Lack of public sector reactivity, measured by the little number of implemented Sargassum management plans.
- Lack of protocols and regional standards specific to sargassum to support safe harvesting, storage and product processing and use.
- No regional policy with regards to access and harvesting of sargassum as a shared or transboundary resource.

Impact:

- Lack of coordination and standards does not help reduce risk perceptions of investors and businesses.

Solutions:

- Creating governance frameworks (policies, management plans, regulations) applicable to Sargassum. Various countries in the Caribbean have declared national states of emergency with respect to sargassum influxes. With the exception of Mexico and the USA, there are no national guidelines regarding sargassum harvesting or management of access conflicts. Only France has classified Sargassum as a public health issue. In 2016, the Caribbean Regional Fisheries Mechanism has developed a protocol for the management of Sargassum.
- Protocols and standards need to be developed to prevent environmental damage and ensure the safety of products.

Encouraging adaptive management practices and plans tailored to local circumstances but which build upon common shared experiences. Internationally, the United Nations Environmental Programme (UNEP) has created a Working Group on *Sargassum* within the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) to identify key *Sargassum* challenges and responses.[88] In 2015 and 2019, CERMES (University of the West Indies) hosted two symposia on sargassum, and in 2019 officials from thirteen Caribbean and Latin American states gathered and

[88] Fidai et al, "A systematic review of floating and beach landing records of Sargassum beyond the Sargasso Sea"

created a 26-point agreement outlining the need for cross-border information sharing on sargassum monitoring, science, education and entrepreneurship.

3 SEAWEED AS BLUE CARBON

3.1 Introduction

3.1.1 Blue carbon, carbon storage and carbon sequestration

Blue carbon or blue carbon ecosystems (BCE)[1] is a concept used to describe the carbon captured by living organisms in coastal ecosystems and stored in biomass and sediments[2]. The blue carbon concept has reached the general public and the policymakers by its inclusion in Intergovernmental Panel on Climate Change (IPCC)'s reports. It has more recently been used by political institutions including the UN (United Nations) and the European Commission to complete a climate policy framework mainly based on terrestrial ecosystems through the LULUCF (land use, land-use change and forestry) concept. Blue carbon ecosystems mainly refer to coastal ecosystems, as the coastal area have the highest biomass concentration and contain most of the sequestered carbon, and as these ecosystems are the most exposed to human actions.

Blue carbon is closely linked with the concept of **carbon sequestration**, which describes the process of taking carbon out of the carbon cycle to store it permanently. To be considered as sequestrated and have a significant effect on climate change mitigation, there is a scientific consensus that carbon must be stored for at least 100 years[3]. In this chapter, we choose to use the term of **carbon pool** used by the IPCC[4] and the European Environmental Agency (EEA). The EEA give the following definition:

> "a carbon pool is a reservoir in the earth system where elements, such as carbon, reside in various chemical form for a period of time. A group of pools are linked in a cycle with flows among the pools influenced by both anthropogenic and non-anthropogenic processes."[5]

[1] Macreadie et al. *Blue carbon as a natural climate solution*, 2022. [access: https://www.nature.com/articles/s43017-021-00224-1]

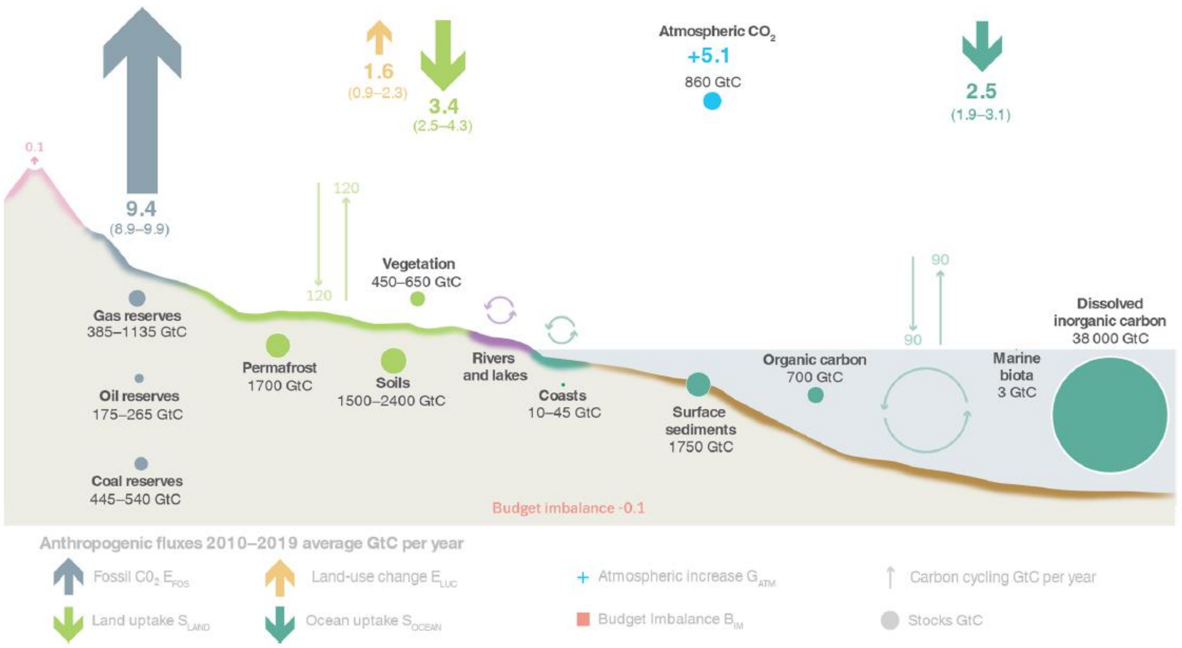
[2] Intergovernmental Panel on Climate Change, 2018., European Environmental Agency. *Carbon stocks and sequestration in terrestrial and marine ecosystems: a lever for nature restoration?* November 2020.

[3] Interviews.

[4] Intergovernmental Panel on Climate Change, 2018.

[5] European Environmental Agency. *Carbon stocks and sequestration in terrestrial and marine ecosystems: a lever for nature restoration?* November 2020

Figure 3.1: Carbon pools in the global carbon cycle



Source: Friedlingstein et al. Global carbon budget 2020.

In the case of the marine carbon cycles, all the carbon stored in living organisms can be considered as an only carbon pool, as well as on another level all the carbon stored in a specific ecosystem. The carbon stock (or quantity of carbon) contained in a carbon pool at a specified time can be measured in MgC or tC (megagrams/tons of carbon)[6]. Only a fraction of the carbon stored in a marine carbon pool is sequestered every year, either in sediments or by being exported to the deep-sea. The **net primary production** (NPP) quantifies a photosynthetic living organism intake of carbon for tissue gross (minus its release due to respiration) per unit of time. Some articles use the alternative concept of net ecosystem production to take into account the carbon intake of a whole ecosystem composed of closely interdependent living organisms. Carbon intake can also be expressed per area (per m^2, km^2 or hectares), in gC/m^2/year or MtC/ha/year. Seaweed carbon **sequestration** (a part of its carbon intake), is often measured in tC/year and can be compared with greenhouse gas (GHG) emissions in tCO_2eq/year (tons of carbon dioxide equivalent per year) using the following ratio: $CO_2 = 44/12 \times C$. The terms of carbon pool and sequestrated carbon are preferred to the concept of “carbon sink”, as they better express the important distinction between temporary and permanent carbon storage. For more clarity we also focus on the flux per year rather than the stocks of carbon at a specified time.

3.1.2 Seaweed as blue carbon among coastal economies

The concept of blue carbon is relatively recent, as it was officially promoted for the first time in 2009 by the UN[7,8&9]. Blue carbon ecosystems have mainly focused on the three major **coastal ecosystems** for which carbon content is easier to quantify, more geographically concentrated and policies are easier

[6] Intergovernmental Panel on Climate Change, 2018.

[7] Nellemann et al. *Blue Carbon - The Role of Healthy Oceans in Binding Carbon*, January 2009. [access: https://www.researchgate.net/publication/288341877_Blue_Carbon_-_The_Role_of_Healthy_Oceans_in_Binding_Carbon]

[8] Macreadie et al. *Blue carbon as a natural climate solution*, November 2021. [access: https://www.nature.com/articles/s43017-021-00224-1]

[9] Lovelock & Duarte. *Dimensions of Blue Carbon and emerging perspectives*, March 2019. [access: https://royalsocietypublishing.org/doi/10.1098/rsbl.2018.0781]

to be taken: mangroves, tidal marshes and seagrass[10]. Soon after the conceptualisation of blue carbon, the UNFCCC (United Nations Framework Convention on Climate Change) published the first method to quantify carbon in **mangroves** in 2011 (clean development mechanism method)[11]. The protection of mangrove ecosystems has seen a significant mobilisation of public of private funding and the creation of a global mangrove alliance gathering major environmental NGOs and research institutions[12]. In 2013, the IPCC issued a wetlands supplement which paved the way to carbon accounting in coastal wetlands and **tidal marshes**[13]. In 2014, a first carbon standard methodology for the restoration of coastal wetlands was published by Verra, one of the major carbon certification companies[14]. More recently, the common agricultural policy for the period 2023-2027 links conditionality with protection of wetlands and peatlands with the explicitly mentioned objective of contributing to climate change mitigation[15]. **Seagrass** ecosystems early identification as coastal endangered biodiverse environment has led to protection efforts in the framework of the EU Habitat Directive adopted in 1992. In 2015, seagrass restoration was first included in a verified carbon standard methodology[16]. Despite being known as the living organism with the highest net primary production, **seaweed** was largely let out of the focus, mainly due to the complex carbon sequestration process involved. Indeed, mangroves, tidal marshes and seagrass ecosystems have in common that the carbon they sequester is mainly stored in the sediments around them, which makes it relatively easy to quantify sequestration thanks to sediment straps. As we will see later, the potentially significant carbon sequestration from seaweed mainly occurs through carbon exports to the deep-sea. This sequestered carbon is difficult to quantify and cannot be linked to the location of a given ecosystem. **Phytoplankton** is another major carbon pool. However, its sparse presence in the water column makes its quantification and targeted action impossible in the short and medium term.

The **identification of seaweed as a potential carbon sink** dates to 1981, before the concept of blue carbon was even created, with the Smith et al. article *Marine macrophytes as a global carbon Sink* published in *Nature*[17]. Interest for **seaweed as a blue carbon solution** has recently been rising after a scientific article has been published giving a first complete estimation of carbon sequestration potential of seaweed, leading to a debate on the issue within the scientific community, followed by a significant media coverage. This potential was further investigated by public institutions, notably in the European Commission's Communication *Sustainable carbon cycles*[18] and more specifically the *Nordic Blue Carbon* report[19] financed by the Nordic council of ministers and led by several academic and research institutions in Northern Europe. This growing interest also highlights an existing public support

[10] European Commission. *Sustainable Carbon Cycles*, Communication to the European Parliament and the Council, 15/12/2021. [access: https://ec.europa.eu/clima/system/files/2021-12/com_2021_800_en_0.pdf]

[11] UNFCCC. *Approved afforestation and reforestation baseline and monitoring methodology: Afforestation and reforestation of degraded mangrove habitats*, June 2011. [access: https://cdm.unfccc.int/UserManagement/FileStorage/GLFDQWIB3ZHPSAMO9C6XR1E74KT205]

[12] Global Mangrove Alliance. "Our Members", official website. [access: https://www.mangrovealliance.org/our-members/]

[13] IPCC. *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*, October 2013 [access: https://www.ipcc.ch/publication/2013-supplement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories-wetlands/]

[14] Verra. "VCS Releases First Methodology to Protect Coastal Wetlands", February 2014. [access: https://verra.org/vcs-releases-first-methodology-protect-coastal-wetlands/]

[15] European Commission. *Sustainable Carbon Cycles*, Communication to the European Parliament and the Council, 15/12/2021. [access: https://ec.europa.eu/clima/system/files/2021-12/com_2021_800_en_0.pdf]

[16] Verified Carbon Standard. *Methodology for Tidal Wetland and Seagrass Restoration*, November 2015. [access: https://verra.org/wp-content/uploads/VM0033-Tidal-Wetland-and-Seagrass-Restoration-v1.0.pdf]

[17] Macreadie et al. *Blue carbon as a natural climate solution*, 2022. [access: https://www.nature.com/articles/s43017-021-00224-1]; Interviews.

[18] European Commission. *Sustainable Carbon Cycles*, Communication to the European Parliament and the Council, 15/12/2021. [access: https://ec.europa.eu/clima/system/files/2021-12/com_2021_800_en_0.pdf]

[19] Nordic Blue Carbon Project. "Blue carbon - climate adaptation, CO2 uptake and sequestration of carbon in Nordic blue forests" September 2020. [access: https://pub.norden.org/temanord2020-541/#47359]

for several projects of seaweed processing at national and EU levels (German BMBF programs, Horizon Europe). The current momentum for seaweed was also pushed by the publication from the Lloyd's Foundation together with several organisations (including Duarte's Ocean 2050) of a *Seaweed Manifesto* in 2020, within the framework of the UN Global Compact, followed in 2021 by a *Seaweed as a Nature-Based Climate Solution* policy statement of the UN Global Compact focusing more specifically on seaweed as a climate solution[20]. More recently, the European Commission's communication *Towards a strong and sustainable EU algae sector* highlighted among other opportunities the role that seaweed farming can play in climate change mitigation[21].

3.2 Sources and methods

3.2.1 Presentation of sources

The state of knowledge on seaweed sequestration potential, both in the natural environment and for seaweed farming, is still sparse. Seaweed carbon farming projects are rare, diverse and based on methodologies of carbon accounting which still have a high level of uncertainty and are far from being unified. In this context, our sources are mainly recent articles from the scientific literature (for the vast majority since 2015, with most articles published after 2019). Our literature review witnessed an overrepresentation of the articles published on the continuity of Duarte et al.'s 2016 article giving the first estimation of the global seaweed sequestration potential, always involving scientists Carlos Duarte and Dorte Krause-Jensen. We tried as much as possible to diversify our sources, with respect to the individuals and universities involved as well as the geographical locations of these individuals and institutions. The literature is much more diversified if we consider the studies focusing on seaweed carbon intake, it is much less on the measurement of carbon sequestration. We found some articles critical on the carbon sequestration potential of seaweed in the natural environment and on the use of seaweed farming for climate change mitigation. In addition to the scientific literature of published articles, we also based our analysis on **reports from public institutions** such as the European Commission, European Environmental Agency, Nordic Council, Helcom and a diverse "**grey literature**" made of unpublished articles and methodologies, NGO and consultancy reports. We used the **FAO (Food and Agriculture Organisation of the United Nations) data** for year 2019 to bring the perspective of the current state of play of seaweed production and farming. Based on this literature review, we decided to conduct **interviews with scientists** involved in the scientific debate on the issue, with Prof. Dr. Dorte Krause-Jensen from Aarhus University (Denmark) on the carbon sequestration potential of seaweed in the natural environment, Dr. Mar Fernandez-Mendez from the Alfred Wegener Institute (Germany), cofounder and lead scientist advisor of *Seafields*, on artificially sinking farmed seaweed for carbon sequestration purposes, Dr. Jean-Baptiste Thomas from the Royal Institute of Technology of Stockholm (Sweden) on its approach of seaweed farming and use based on life cycle assessment and Prof. Dr. Jean-Pierre Gattuso from Sorbonne University/CNRS (France) on seaweed carbon mitigation potential among other coastal ecosystems.

3.2.2 Presentation of available methods

We could identify a large range of methods relevant for the assessment of seaweed blue carbon potential, which we arbitrarily distinguished in 5 broad categories for more clarity:

[20] UN Global Compact. *Seaweed as a Nature-Based Climate Solution Vision Statement*, 2021. [Access: https://www.unglobalcompact.org/library/5974]

[21] European Commission. *Towards a strong and sustainable EU algae sector*, Communication to the European Parliament, the Council, the European economic and social committee and the committee of the regions, 15/11/2022. [access: https://oceans-and-fisheries.ec.europa.eu/system/files/2022-11/COM-2022-592_en.pdf]

- Methods able to compare and quantify individual seaweed carbon intake using sampling, cultivation and in-vitro oxygen measurement, with for some studies further testing on the influence of various environmental parameters (light, dissolved carbon concentrations…);
- Methods able to measure carbon and oxygen flux of ecosystems in the natural environment using acoustic instruments (eddy covariance and benthic chambers) coupled with remote sensing (oxygen, pH measurements) and observations;
- Methods using water and sediment sampling, genetic analysis and Remotely Operated Vehicles (ROV) observations to quantify the amounts of sequestered carbon in on-site sediments or witness the presence of allogenous carbon in deep-sea environments, where it is considered as sequestered;
- Methods compiling data and using theoretical ratios (chemical exchanges between carbon pools, dry weight/carbon content ratio, carbon content/atmospheric CO_2 conversion ratio) able to give aggregate estimations of the carbon flux and sequestration on the global level;
- Methods assessing the carbon footprint of seaweed farming, transport, processing and use, notably by using life cycle assessment, which can be complemented by technoeconomic or sociological analysis.

Methods measuring carbon intake of particular seaweed species are often based on **seaweed sampling** and oxygen measurement in laboratory. For one of these, seaweed plant sections are inserted in bottles filled with seawater and incubated 3 hours. Their **oxygen content** is then measured by titration and compared to the measurement made in control bottles filled with ambient water (including "ambient" plankton). This experiment witnesses differences and quantifies the amount of CO_2 taken from the bottle by the seaweed plant sections[22]. Another study samples of different seaweed types (green, brown and red) from a natural environment, remove the associated plankton and algal spores, and incubates these samples in CO_2-enriched water with various levels of dissolved CO_2. Samples are also more or less exposed to the light. Gross primary productivity can be determined from the oxygen production values, and net primary productivity from the changes in **dissolved carbon concentrations**. Differences can be witnessed depending on the variation of environmental parameters[23].

Among the acoustic methods used to quantify carbon and oxygen flux on an ecosystem in the natural environment (or in farm) **aquatic eddy covariance** is one the most used method since 2014, along with **benthic chambers** that were used since a longer time. Aquatic eddy covariance (AEC) is able to measure carbon and oxygen flux of ecosystems in the natural environment on areas ranging from 10 to 100 m^2 using acoustic measurement tools (doppler velocimeter) combined on a floating platform with an oxygen probe[24][25]. A benthic chamber can measure in-situ seaweed carbon intake from photosynthetically active radiation. In addition to **oxygen probes**, acoustic instruments can be combined with **pH and pCO_2 sensors**. These techniques allow a measurement of carbon intake in natural conditions, where it makes much more sense to study the performance of seaweed ecosystems combining different living organisms than individual seaweed species. The combined use of acoustic instruments and sensors is limited by its high costs of deployment, and the state-of-the-art acoustic instrument are not fit for high depths. Their use or planned use is limited to low-depth coastal areas[26].

[22] Mashoreng et al. *Cultivated seaweed carbon sequestration capacity*, December 2019. [access: https://www.researchgate.net/publication/337713181_Cultivated_seaweed_carbon_sequestration_capacity]

[23] Kaladharan et al. *Carbon sequestration by a few marine algae: observation and projection*, June 2009. [access: http://eprints.cmfri.org.in/2212/1/Kaladharan_107-110.pdf]

[24] Long & Nicholson, *Surface gas exchange determined from an aquatic eddy covariance floating platform*, December 2017. [access: https://aslopubs.onlinelibrary.wiley.com/doi/full/10.1002/lom3.10233]

[25] Berg et al. *Aquatic Eddy Covariance: The Method and Its Contributions to Defining Oxygen and Carbon Fluxes in Marine Environments*, September 2021. [access: https://www.annualreviews.org/doi/abs/10.1146/annurev-marine-042121-012329]

[26] Interviews.

Given the complex mechanism of carbon sequestration from seaweed, these methods can only give an estimation of a seaweed ecosystem net primary production rather than its carbon sequestration.

The 2016 article from Carlos Duarte and Dorte Krause-Jensen[27] investigating carbon sequestration of seaweed ecosystems worldwide use data from **submarine observation** of ROV to witness the presence of significant quantities of seaweed material in deep-sea environments. The 2019 Ortega et al. article, also involving Carlos Duarte and Dorte Krause-Jensen, uses more recent samples from Tara Oceans and Malaspina expeditions bearing **genetic signatures** of different seaweed species. Genetic-based monitoring of carbon is also identified by a 2020 desk-study of Wageningen University through the method of **E-DNA biomonitoring** able to give the detailed composition of biological communities as well as the determinants of sedimentation, and sequestration[28]. An ongoing project evaluating carbon sequestration in seaweed farms' sediments within the Ocean 2050 initiative uses a new method of **PCR quantitative DNA** analysis which has also been tested with several samplings in Hiroshima Bay by a team of Japanese scientists[29]. With this method, DNA isotope can potentially provide an identification on the origin of the carbon contained in the sediments[30]. These techniques can witness the presence of material exports but can't give a quantification of carbon sequestration from seaweed farms or ecosystems[31]. The PCR quantitative DNA analysis led within the Ocean 2050 initiative gave estimations on the carbon sequestered in the farm's sediments, without taking into account carbon exports[32].

Quantifications of carbon sequestration in deep-sea environment have been conducted thanks to **theoretical modelling** of dispersion and flux between the different carbon pools[33] based for the 2016 Duarte et al. article on a very broad and diverse literature review. The authors admit significant uncertainties due to the sparse data, which are translated by large uncertainty ranges[34]. In addition to the estimations of carbon exports to the deep-sea in natural environment, we could identify **key ratios** used to determine the mitigation potential of wild and farmed seaweed. As mentioned earlier, the European environmental agency uses a ratio to convert organic carbon content to gaseous carbon dioxide such as **CO_2 = 44/12 x C**[35]. In the Duarte et al. 2017 article, 2 mean ratios are used to convert seaweed weight to seaweed dry weight such as **dry weight = 0,1 x full weight** and seaweed dry weight to organic carbon content, such as **C = 0,248 x dry weight**[36]. It is noted that the carbon-to-CO_2 ratio is widely used while the weight-to-carbon ratio to our knowledge only used in one article.

Finally, we identified methods focusing on carbon sequestration through seaweed farming and use. Methods of carbon accounting in supply chains such as **life cycle assessments** (LCAs) are applied in

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[27] Duarte et al. *Global estimates of the extent and production of macroalgal forests*, 2022. [access: https://onlinelibrary.wiley.com/doi/10.1111/geb.13515]

[28] Veraart et al. *Methods to assess Blue Carbon Potential of Seaweed Culture at the North Sea: feasibility study*, March 2020 [access: https://edepot.wur.nl/537676]

[29] Hamaguchi et al. *Development of Quantitative Real-Time PCR for Detecting Environmental DNA Derived from Marine Macrophytes and Its Application to a Field Survey in Hiroshima Bay, Japan*, 2022. [access: https://www.mdpi.com/2073-4441/14/5/827/htm]

[30] Interviews.

[31] Ibid.

[32] Carlos Duarte in "Seaweed Conference" (video), Monaco Ocean Week, March 2022. [access: https://www.youtube.com/watch?v=kv5vCHnew6Q&t=3422s]

[33] Duarte et al. *Global estimates of the extent and production of macroalgal forests*, 2022. [access: https://onlinelibrary.wiley.com/doi/10.1111/geb.13515]

[34] Interviews.

[35] European Environmental Agency. *Carbon stocks and sequestration in terrestrial and marine ecosystems: a lever for nature restoration?* November 2020

[36] Duarte et al. *Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation*? 2017. [access: https://www.frontiersin.org/articles/10.3389/fmars.2017.00100/full]

these cases. LCAs take into account part (cradle-to-gate) or the whole of the supply chain, including end-of-life (cradle-to-grave) and recycling/reuse (cradle-to-cradle). Several studies have applied LCAs to farmed seaweed, focusing either on seaweed farming[37] or seaweed-based products processing[38]. These LCAs do not cover the farmed seaweed's whole life cycle, and are still explorative studies. However, LCAs applied to seaweed are likely to develop in the near future building on the experience gained on LCAs applied to other bioeconomy sectors (wood, energy, etc.)[39]. **Consequential LCAs** are particularly relevant to the seaweed economy as they take into account the changes in the environment, from the preexistent ecosystem to the farmed seaweed ecosystem. A concept of sea-use change could be potentially developed[40]. Ocean Vision's *Sinking seaweed report* also highlights the central role of LCAs while stressing the need for additional sociological and psychological analyses related to social acceptance, risk perception, risk-risk tradeoffs, analysis on environmental justice and equity and technoeconomic analyses before considering a farming project[41].

3.3 STATE OF PLAY OF KNOWLEDGE ON CARBON STORAGE AND SEQUESTRATION IN THE NATURAL ENVIRONMENT

While the scientific literature on the issue has been growing significantly in the recent years, knowledge on the carbon sequestration potential of seaweed remains sparse. Most of the studies consider seaweed ecosystems as being net sequestrators of carbon. Estimations of their carbon sequestration capacities vary significantly, following differences of methods, type of ecosystems and geographical locations. One series of articles from the university of Tasmania criticises the assumption that seaweed ecosystems are net sequestrators of carbon.

3.3.1 Marine carbon cycles and orders of magnitude

The scientific literature agrees on the general functioning of carbon marine cycle and on the mechanisms involved in carbon sequestration from seaweed. However, scientists diverge on the respective importance of factors and the estimated numbers. Seaweed ecosystems are part of one of the **carbon pools in coastal ecosystems**[42] between which carbon is mobilised and exchanged: dissolved inorganic carbon and dissolved organic carbon (DIC and DOC) in seawater, inorganic carbon in shells and skeletal and organic carbon in living marine organisms (in various vegetal and animal species, including shellfish and seaweed), particulate organic carbon in sediments (carbonates or POC) and sedimentary organic carbon (SOC). Each of these carbon pools plays a role in sequestrating carbon in the ocean. The main equilibrium of the marine carbon cycle is the exchange of gas between the atmosphere and the ocean, through which atmospheric CO_2 is dissolved in the form of DIC and carbonate ions. Part of the DIC is used by marine plants (including seaweed and seagrass) to grow, and part of the carbonate ions is used by marine organisms as building material for shells and skeletons,

[37] Thomas et al. *A comparative environmental life cycle assessment of hatchery, cultivation, and preservation of the kelp Saccharina latissima*, 2021. [access : https://academic.oup.com/icesjms/article/78/1/451/5892999]

[38] Ekman-Nilsson et al. *Life cycle assessment of a seaweed-based biorefinery concept for production of food, materials, and energy*, 2022. [access: https://www.sciencedirect.com/science/article/pii/S2211926422000960]

[39] Interviews.

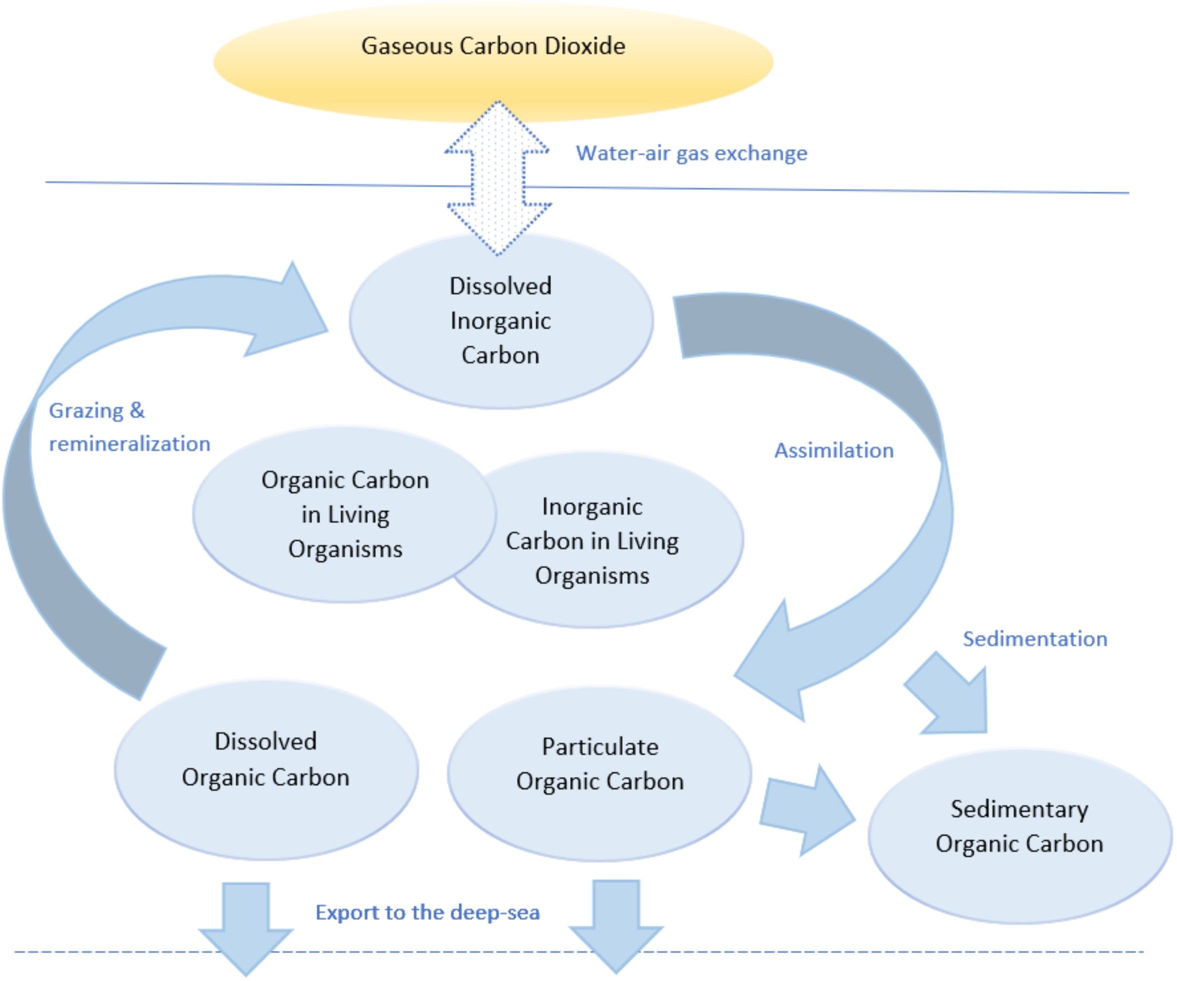
[40] Ibid.

[41] Ocean Visions. *Answering critical questions about sinking macroalgae for carbon dioxide removal*, 2022.

[42] Watanabe et al. *Analysis of the seawater CO2system in the barrier reef–lagoon system of Palau using total alkalinity-dissolved inorganic carbon diagrams*, 2006. [access https://aslopubs.onlinelibrary.wiley.com/doi/epdf/10.4319/lo.2006.51.4.1614]

both processes immobilising carbon in these two carbon pools[43]. In the natural environment, only a small part of the seaweed's carbon content will ultimately be sequestrated by being buried under the algal bed and ultimately sedimented. Most of it will be grazed by marine animals or re-mineralised by microbes while a significant part is exported to the deep-sea as organic tissue or in the form of DOC and POC. Grazing and remineralisation leads to a quick recycling and release of carbon, whereas the carbon exports reaching the deep-sea are stored long enough to be considered as sequestered[44].

Figure 3.2: Carbon cycle in marine environnement



Source: EUMOFA, based on Krause-Jensen & Duarte. *Substantial role of macroalgae in marine carbon sequestration* (2016) and Briesemeister. *Swedish blue carbon assets in coastal vegetated ecosystems* (2021)

The scientific community agrees on the fact that seaweed has the highest production per area (or gross primary production) among coastal ecosystems, meaning that a mean area of seaweed ecosystem convert more carbon from the atmosphere to organic tissue than any other ecosystem. According to the most recent (2022) estimations seaweed ecosystems occupy an **area** of **6 to 7,2 Mkm²** of the

[43] Briesemeister. *Swedish blue carbon assets in coastal vegetated ecosystems. A compilation of knowledge*, 2021. [access https://gupea.ub.gu.se/bitstream/handle/2077/69661/gupea_2077_69661_1.pdf;jsessionid=285762E6D1C7249DA8A6840203673031?sequence=1]

[44] GHG management institute, "Kelp and carbon sequestration: exporting terrestrial GHG accounting to the deep-sea, September 2018. [access: https://ghginstitute.org/2018/09/06/kelp-and-carbon-sequestration-exporting-terrestrial-ghg-accounting-to-the-deep-sea/]

global ocean along the coastline[45], their maximal extension potential based only on light availability goes up to 12,5 Mkm^2.[46] To note, the following carbon storage and sequestration numbers are based on a previous estimation of 3,5 Mkm^2.[47] The mean carbon **net primary production** (NPP) from seaweed is globally **420 gC/m2/year**, with significant variations depending on the ecosystem and the environmental factors. Multiplied by the estimated surface and taking into account the uncertainties, the global net primary production from seaweed is comprised between **1 020 to 1 960 MtC/year**[48] (1 521 MtC/year according to the 2016 estimate, 1320 MtC/year in the 2022 estimate). These orders of magnitude represent approximately half of the net primary production from the whole Amazonian Forest (290 to 3 400 MtC/year)[49]. The estimated carbon sequestration from seaweed ecosystems reaches 173 MtC/year[50], with a significant range of uncertainty from **61 to 268 MtC/year**. These amounts can be converted to **224 to 983 MtCO$_2$/year**, which represents 0,4 to 2,5% of global anthropogenic GHG emissions (over 45 000 MtCO$_2$eq/year in 2019)[51] or 5,6 to 24,5% of EU emissions (approximately 4 000 MtCO$_2$eq/year)[52]. This level of sequestration would also match the annual sequestration from tidal marshes, mangroves and seagrass combined[53], and approximately a tenth of the ocean total carbon uptake (9 000 MtCO2eq/year), which account for slightly less than the total land carbon uptake (12 000 MtCO2eq/year)[54]. However, there is no scientific consensus on this high range of sequestration potential, and a series of articles from the university of Tasmania notably demonstrate the uncertainty of considering seaweed ecosystems as net sequestrators of carbon, pointing out the need to assess carbon net emissions from the interlinked ecosystems, including phytoplankton and fauna. These studies also highlight the need to take into account the significant amount of carbon from coastal exported material being used by seaweed to grow beyond the carbon from water-air gas exchange[55].

[45] Duarte et al. *Global estimates of the extent and production of macroalgal forests*, 2022. [access: https://onlinelibrary.wiley.com/doi/10.1111/geb.13515]

[46] Gattuso et al. *Light availability in the coastal ocean: Impact on the distribution of benthic photosynthetic organisms and contribution to primary production*, 2006 [access: https://bg.copernicus.org/articles/3/489/2006/bg-3-489-2006.html]

[47] Duarte et al. *Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation*? 2017. [access: https://www.frontiersin.org/articles/10.3389/fmars.2017.00100/full]

[48] Duarte et al. *Global estimates of the extent and production of macroalgal forests*, 2022. [access: https://onlinelibrary.wiley.com/doi/10.1111/geb.13515]

[49] Ibid.

[50] Krause-Jensen & Duarte. *Substantial role of macroalgae in marine carbon sequestration*, 2016. [access: https://www.nature.com/articles/ngeo2790]

[51] World Bank/Climate Watch. Data, 2020 [access: https://data.worldbank.org/indicator/EN.ATM.GHGT.KT.CE]

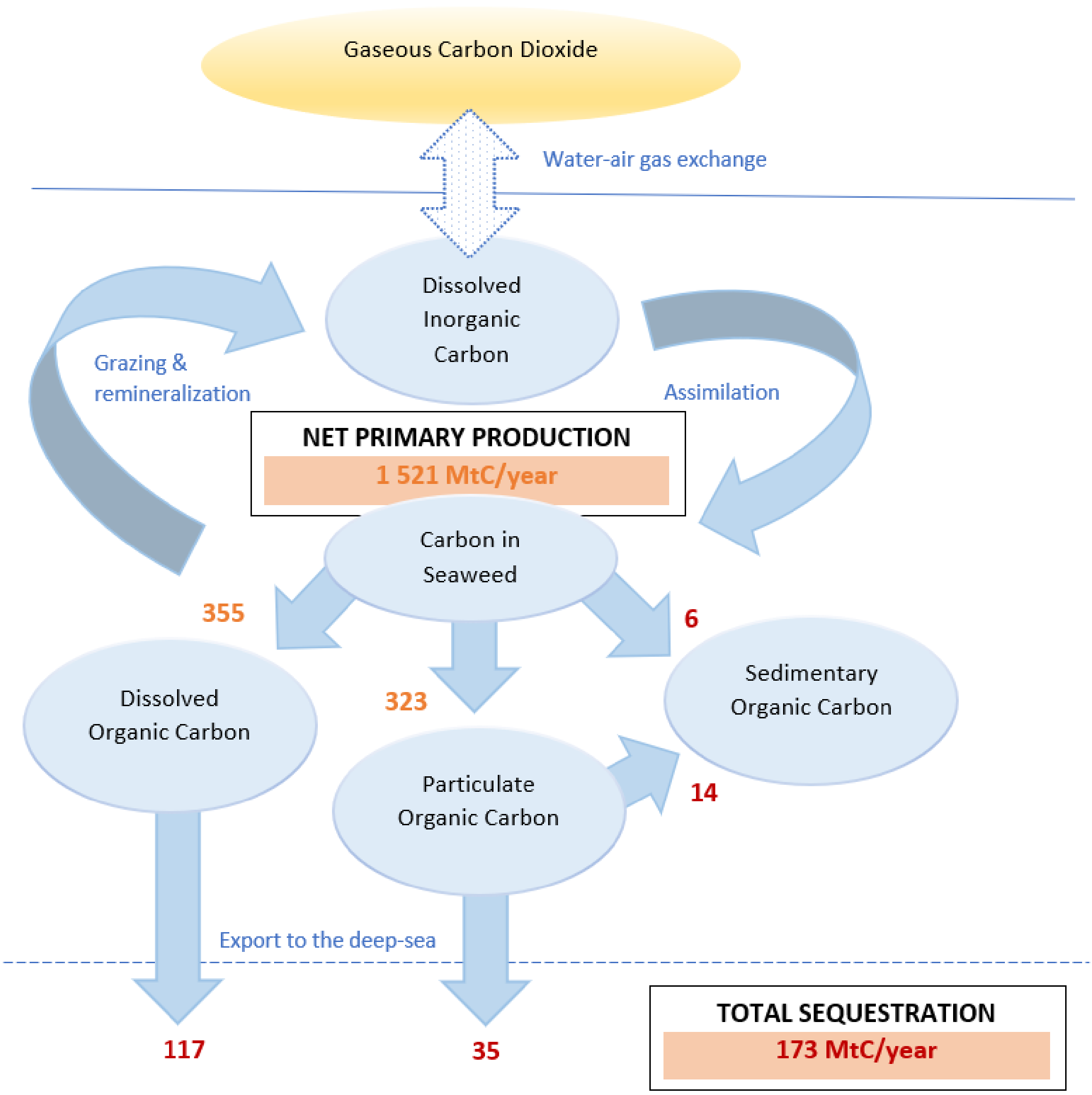
[52] European Environmental Agency. "Total greenhouse gas emission trends and projections in Europe", October 2022. [access: https://www.eea.europa.eu/ims/total-greenhouse-gas-emission-trends]

[53] Krause-Jensen et al. *Sequestration of macroalgal carbon: the elephant in the Blue Carbon room*, 2018. [access: https://royalsocietypublishing.org/doi/10.1098/rsbl.2018.0236]

[54] Friedlingstein et al. *Global carbon budget 2020*, 2020.

[55] Gallagher et al. *Seaweed ecosystems may not mitigate CO2 emissions*, 2022.

Figure 3.3: Global estimations for seaweed net primary production and sequestration



Source : EUMOFA, based on Krause-Jensen et al. *Substantial role of macroalgae in marine carbon sequestration* (2016)

The scientific literature does not give orders of magnitude of seaweed net primary production and sequestration in Europe or in the European Union. The Nordic Council of Ministers (bringing together ministers of Denmark, Sweden, Finland, Norway, Faeroe islands, Island, Greenland and Aland) financed an evaluation of the regional seaweed and seagrass carbon sequestration potential which was released in 2020[56]. Its detailed evaluation of seaweed net primary production and sequestration is based on the same hypotheses as the above-mentioned orders of magnitude, with Dorte Krause-Jensen participating in both estimations. According to this study, seaweed ecosystems in **Nordic countries** (the above-mentioned countries excluding Greenland) have a **net primary production** of **4,9 MtC/year** and **sequestrate** of 0,95 MtC/year, equivalent to **3,5 MtCO$_2$/year**. This carbon sequestration potential represents close to 2% of these same countries' annual GHG emissions.

[56] Nordic Blue Carbon Project. "Blue carbon - climate adaptation, CO2 uptake and sequestration of carbon in Nordic blue forests" September 2020. [access: https://pub.norden.org/temanord2020-541/#47359]

The scientific community agrees on the fact that the range of uncertainty to quantify net primary production and to a larger extend sequestration remains considerable. All articles also highlight the high variability of these parameters depending on both the ecosystems and environmental parameters.

3.3.2 Net primary production by type of ecosystem and environmental parameters

Several articles compare the carbon intake of **different seaweed ecosystems** (families, genus and species, type of aggregation). Based on individual seaweed net primary production, the best performing species are brown seaweed/kelp (especially Ecklonia genus) in temperate areas (Korea, Europe) and red seaweed (especially Eucheuma genus) in the tropical areas (Indonesia)[57]. Among the best performing brown algae, a study highlights significant differences between species of the same genus, identifying a "carbon sink" per 100 m of rope of 43,5 kgC for Ecklonia cava, compared to 88,9 kgC for Ecklonia stolonifera, making a factor 2 difference of carbon intake potential between the two species (respectively 0,78 and 1,60 $kgCO_2eq/m^2/year$)[58]. The best performing ecosystems are brown seaweed forests, with an estimated net primary production of 536 $gC/m^2/year$, before the algal turfs (low lying aggregation of various species of short algae) at 321 $gC/m^2/year$, the coralline algae and rhodolite beds at 207 gC/m2/year and the algal beds, for which red algae are performing better than brown and green algae, from 194 to 134 $gC/m^2/year$[59]. These numbers admit significant ranges of uncertainty shown in Figure 3.4: Net primary production in natural environment by vegetation type, excluding floating algae (in gC/m2/year). They still allow the comparisons between ecosystems.

Figure 3.4: Net primary production in natural environment by vegetation type, excluding floating algae (in gC/m2/year)

[57] Erlania et al. *The Use of Seaweeds Aquaculture for Carbon Sequestration: A Strategy for Climate Change Mitigation*, June 2015. [access: https://www.researchgate.net/publication/280496133_The_Use_of_Seaweeds_Aquaculture_for_Carbon_Sequestration_A_Strategy_for_Climate_Change_Mitigation] ; Mashoreng et al. *Cultivated seaweed carbon sequestration capacity*, December 2019. [access: https://www.researchgate.net/publication/337713181_Cultivated_seaweed_carbon_sequestration_capacity]; Hickson R. *Integrated Multi-Trophic Aquaculture for Carbon Sequestration and Shellfish Production*, October 2018. [access: https://bluecarbon.co.nz/wp-content/uploads/2020/05/Seaweed-Carbon-Sequestration-off-the-Continental-Shelf-of-NZ.pdf]

[58] Hickson R. *Integrated Multi-Trophic Aquaculture for Carbon Sequestration and Shellfish Production*, October 2018. [access: https://bluecarbon.co.nz/wp-content/uploads/2020/05/Seaweed-Carbon-Sequestration-off-the-Continental-Shelf-of-NZ.pdf]

[59] Pessarrodona et al. *Global seaweed productivity*, September 2022. [access: https://www.science.org/doi/10.1126/sciadv.abn2465]

Source: EUMOFA, based on Pessarrodona et al. *Global seaweed productivity* (2022)

Beyond the NPP performance of different ecosystems, key **environmental parameters** impacting NPP have also been identified for the main ecosystems. Considering intertidal marine forests of brown macroalgae, the main influential factor is the maximum wave energy, followed by nitrate concentration. For subtidal marine forests of brown algae, the predominant parameter is the minimum temperature, followed by nitrate concentration and to a lesser extend light. For algal turfs (brown and other algae), the maximum wave energy is the predominant factor, before salinity variation and maximum temperature. Wave energy, nitrate concentration and temperatures have a significant impact contributing up to 20 (temperature)- 40% (wave energy) to the net primary production. Some of the environmental parameters will be significantly altered by climate change. It is estimated that sea warming already led to an increase of seaweed biomass and productivity in polar regions, while it decreased carbon assimilation and export in temperate regions due to coastal ecosystems facing significant losses and reconfiguration. Mixed effects are witnessed in the tropical areas.[60] The increased number and intensity of extreme meteorologic events may also lead to significant losses of carbon intake from seaweed.

These environmental factors are also limiting the area where seaweed is actually viable. The main factors limiting the extension of seaweed ecosystems are light availability, substrate availability, with for a majority of seaweed species salinity variations.[61]

3.3.3 Assessment on the sequestration from wild seaweed ecosystems in Europe

Apart from the broad estimations on the global level, seaweed carbon sequestration potential in the natural environment is largely unknown at regional levels or for specific ecosystems.

The Nordic Council of Minister's study is the only identified source to give a regional estimation for net primary production and sequestration potential of seaweed ecosystems in the **Nordic countries'** coastal area. Two seaweed ecosystems are taken into account: kelp forests and algal beds, while algal turfs and rhodolite/coralline algae as well as kelp forests are being considered as non-significant under these latitudes. With an area of 10 900 km2, **kelp forests** in Nordic countries have a net primary production of 3,3 MtC/year and sequestrate 0,7 MtC/year, equivalent to **2,7 MtCO_2/year**. With an area of 5 500 km^2, **algal beds** have a net primary production of 1,6 MtC/year and sequestrate 0,2 MtC/year, equivalent to **0,8 MtCO_2/year**. If we choose to exclude the Norwegian coast to get an estimation of the Nordic EU Member States sequestration, kelp forests sequestrate 0,9 MtCO_2/year and algal beds 0,4 MtCO_2/year.

Seaweed ecosystems degradation is difficult to quantify in terms of areas lost. These ecosystems are also far more resilient than other coastal ecosystems such as tidal marshes, mangroves, seagrass or corals and are among the first species to colonise other degraded habitats such as coral reefs[62]. The main factors seaweed communities' reconfigurations are climate change and invasive species, adding to the degradation from trampling, mainly affecting brown algae, harvesting, habitat modifications due to human constructions, overgrazing and eutrophication[63].

[60] Pessarrodona et al. *Global seaweed productivity*, September 2022. [access: https://www.science.org/doi/10.1126/sciadv.abn2465]

[61] Interviews.

[62] Interviews.

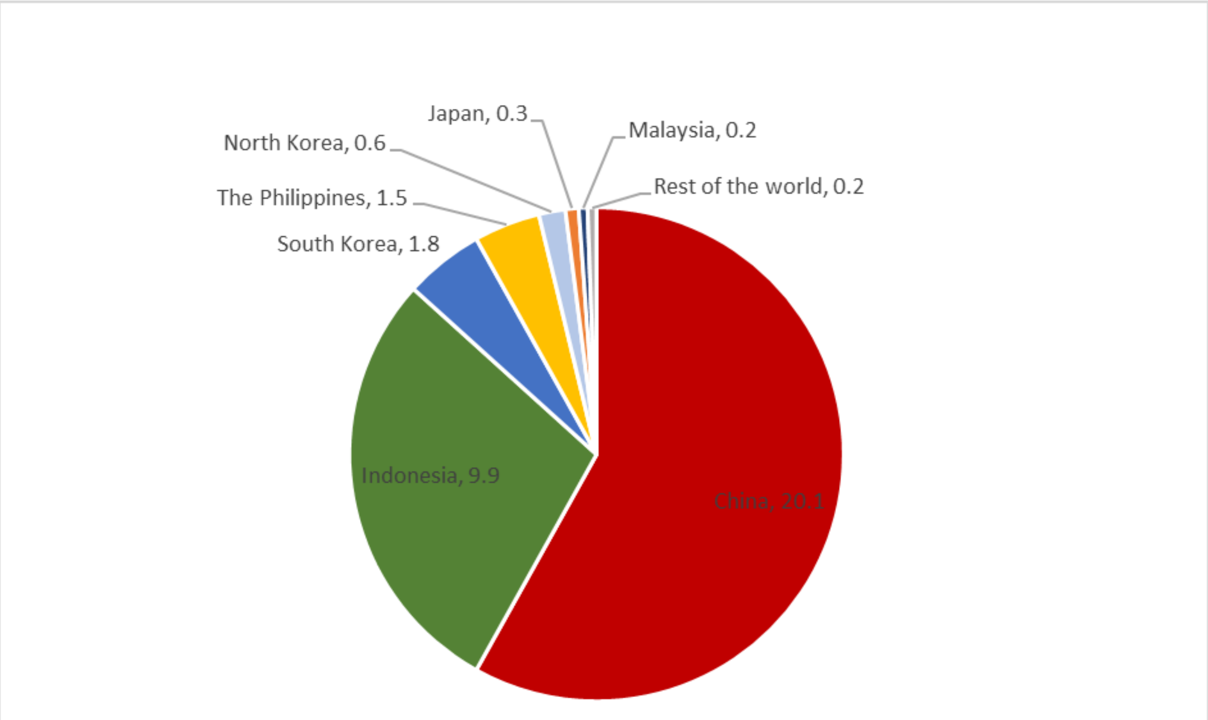
[63] Mineur et al. *European seaweeds under pressure: Consequences for communities and ecosystem functioning*, 2021.

3.4 State of play of knowledge on seaweed farming as carbon sequestration

3.4.1 State of play of seaweed farming and harvesting

Seaweed farming is a **traditional aquaculture activity** whose primary goal is food production. China is the largest producer country with a farmed seaweed production of 20,1 Mt in 2019, Indonesia being second with 9,9 Mt. Both countries taken together account for 87% of the total world production. South Korea (1,8 Mt), the Philippines (1,5 Mt), North Korea (0,6 Mt), Japan (0,3 Mt) and Malaysia (0,2 Mt) are other significant seaweed producers. The remaining countries taken together account for less than 0,6% of total world production (0,2 Mt). Seaweed production is divided between two almost equal shares of red algae (18 Mt) and brown algae (16,5 Mt), with significantly less significant productions of green algae (0,01 Mt), which is account for a lower volume than the production of the microalgae spirulina (0,05 Mt). The most produced species are the red algae nori (2,9 Mt) and the brown algae wakame (2,5 Mt). Almost all farmed seaweed production (more than 99%) comes from mariculture, with only 0,6% of seaweed from brackish (0,1 Mt) or freshwater (0,05 Mt). Harvesting from wild adds 1,08 Mt to the 34,7 Mt of farmed seaweed production, making 3% of the total seaweed production. Chile is the largest producer of harvested seaweed, making with 0,4 Mt 37% of the total. Chile is followed by China (0,17 Mt), Norway (0,16 Mt) and the European Union countries taken together (0,08 Mt, or 8% of the total production from wild harvesting)[64].

Figure 3.5: Farmed seaweed production by country in 2019 (millions of tonnes)



Source: FAO

[64] FAO, 2019.

3.4.2 Orders of magnitude on sequestration potential from human-led seaweed production

The global human-led **production** of seaweed is approximately 36 Mt of macroalgae per year[65], mainly (96,5%[66]) from aquaculture. Considering a theoretical situation in which the entire global seaweed production would be "neutralised" without any additional emission or substitution by other food sources, an upper limit of 0,68 MtC/year – equivalent to 2,48 MtCO_2eq/year – could be **sequestrated** thanks to current production levels[67]. This order of magnitude could potentially occur if the current surface of 2 000 km^2 dedicated to seaweed farming were to be doubled with extra seaweed production exclusively dedicated to carbon sequestration. A maximal extension potential is given by seaweed specialist Carlos Duarte, who estimated in a press statement that seaweed farming "could theoretically be extended to 4 Mkm^2 of the oceans while delivering positive impacts on the environment"[68]. With this maximal extension, up to 4 900 MtCO2eq/year could be sequestered by "neutralising" the entire production, which can be compared to the 6 000 MtCO2eq/year emitted worldwide with land-use change. Before these hypothetical uses of current or projected productions, an ongoing evaluation from the Ocean 2050 initiative is investigating carbon sequestration already occurring in existing seaweed farms, based on on-site sediment sampling. The first results presented during Monaco Ocean Week in March 2022 give an average additional carbon sequestration due to farming activities of 1,4 tCO_2eq/ha/year[69]. This limited potential, comparable to good agricultural practices on land, does not take into account potentially more significant carbon exports.

Applying the same hypothesis of dedicating the entire production for carbon sequestration purposes to current levels of farmed seaweed production outside Asia (less than 0,2 Mt), carbon mitigation from non-Asian seaweed farms would only reach 15 000 tCO2eq/year. With the same hypothesis applied to current **EU** levels of production from **harvesting (86 000 t) and farming (613 t)**[70] **combined**, seaweed production would only sequestrate **7 200 tCO2eq/year**. A year of "neutralising" the entire farmed and harvested seaweed EU production for sequestration purposes would only account for 0,002% of the new EU objective to remove 301 MtCO_2eq between 2026 and 2030 in the LULUCF sector[71].

If a maximal **extension of seaweed farming** in the EU could be theoretically estimated in the same way as Duarte's global estimation, all interviewed scientists agreed on the very limited potential extension of farming surfaces left by already optimised EU coastal areas, light availability, space and nutrient availability being main critical limits. They also agree on the insufficient level of knowledge on the environmental impacts of "sea-use-change" from existing marine environments to farmed seaweed ecosystems. Competition for space, nutrient and light is less pressing in the case of open-sea oceanic projects, such as those planned in the Atlantic (including *Kelp Blue*, *Seafields*), but these projects face other challenges in terms of dealing with lower nutrient concentrations (e.g., in open ocean areas of

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[65] Araújo et al. *Current Status of the Algae Production Industry in Europe: An Emerging Sector of the Blue Bioeconomy*, January 2021. [access: https://www.frontiersin.org/articles/10.3389/fmars.2020.626389/full]

[66] Ibid.

[67] Duarte et al. *Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation*? 2017. [access: https://www.frontiersin.org/articles/10.3389/fmars.2017.00100/full]

[68] Carlos Duarte. "Seaweed a model solution for fighting climate change", October 2021. [access: https://www.globenewswire.com/en/news-release/2021/10/07/2310625/0/en/Seaweed-a-model-solution-for-fighting-climate-change.html]

[69] Carlos Duarte in "Seaweed Conference" (video), Monaco Ocean Week, March 2022. [access: https://www.youtube.com/watch?v=kv5vCHnew6Q&t=3422s]

[70] FAO, 2019.

[71] European Commission. "European Green Deal: EU agrees to increase carbon removals through land use, forestry and agriculture", November 2022. [access: https://ec.europa.eu/commission/presscorner/detail/%20en/ip_22_6784]

Atlantic), with logistical issues for harvesting, transport and processing and with an uncertain overall economic viability[72].

While reviewing ocean-based solutions for climate change mitigation, the 2019's Hoegh-Guldberg et al. article *The Ocean as a solution to climate change*[73] gives a **global mitigation potential** from farmed seaweed of 10 to 20 $MtCO_2eq$/year for 2030 and 50 to 290 MtCO2eq/year for 2050,[2] while highlighting uncertainties on the expansion of the industry and on the proportion of the production which could be sequestered, and without any estimation on the surface needed to obtain these levels of production. This same article considers the available data on the mitigation impact of seaweed ecosystem conservation and restoration as insufficient to give estimations on these actions. Among the **most ambitious projects** to date[74], *Kelp Blue* plans to operate large-scale seaweed farming in the open-sea (30 to 100 km from the Namibian city of Lüderitz), with the 2029 goal to mobilise **70 000 hectares** for an estimated sequestration of **1 $MtCO_2$/year**[75]. It is unclear whether this estimation bets on a complete substitution from existing consumption products to seaweed-based ones, which could significantly minor its impact as the planed final production includes 125 000 tons of fish feed, 235 000 tons of fertiliser, 150 000 tons of alginate (used for cosmetics) and 42 000 tons of textile fiber[76].

3.4.3 Options to use human-led seaweed production for carbon storage and sequestration

Among the possible uses of human-led seaweed production for climate change mitigation purposes, seaweed "neutralisation" or **artificial direct sequestration** has been theoretised in the scientific literature, planned in prospective projects, and is even already operating with a few pilot projects[77] The main options foreseen are different modalities of seaweed sinking[78]. The other use foreseen in the scientific literature and already operating in a few projects is seaweed processing with the perspective to offer a lower-carbon seaweed-based **substitute to existing products**. The planned productions from seaweed processing include food, feed, fertilisers, cosmetics, biopolymers, biofuels and biogas. Interestingly, the production of fertilisers and biochar offers both a substitute to fossil-fuel based products and an opportunity for sequestration in the agricultural land.

Beyond the respective limits of seaweed farming projects in coastal areas and in the open sea, the above-mentioned uses have serious limitations in terms of climate change mitigation impacts, of potential negative environmental impact and of cost effectiveness –all this needs further assessments.

Sinking seaweed for sequestration purposes so far has no proof of positive environmental, climate nor economic benefits. It also faces the challenge of making sure the seaweed is not grazed and re-mineralised before it reaches the deep-sea. A project such as *Seafields* plans to address this risk of degradation by baling[79] seaweed before sinking it. This technique has however never been implemented

[72] Interviews.

[73] Hoegh-Guldberg et al. *The Ocean as a solution to climate change: Five opportunities for action*, September 2019. [access: https://www.researchgate.net/publication/335984900_The_Ocean_as_a_Solution_to_Climate_Change_Five_Opportunities_for_Action]

[74] Interview Mar Fernandez-Mendez

[75] Kelp Blue. "About", official website. [access: https://kelp.blue/about/]

[76] Ibid.

[77] E.g., Running Tide project based in Maine (USA) https://www.runningtide.com/

[78] Interviews.

[79] Baling is a process that compresses material into a block (bale) which is secured by plastic or wire strapping. Further information available on page 13 of the following report: https://oceanvisions.org/wp-content/uploads/2022/10/Ocean-Visions-Sinking-Seaweed-Report_FINAL.pdf

yet and may be logistically complicated, as seaweed sinking projects are located on the open-sea[80]. *Running Tide* project operates kelp seeding of floating platforms to be sunken under a given weight. This solution is logistically less complicated but its contribution to sequestration is very uncertain due to the remineralisation and grazing occurring before seaweeds reach the deep-sea. Providing an artificial vessel to a given seaweed specie could also prove problematic and lead to an uncontrolled spread. Beyond the problem of making sure carbon reaches the bottom of the sea, too little is known about deep-sea ecosystems to predict the consequences of such an input of significant quantities of organic material. The fact that deep-sea water only reaches the surface after 700 to 1000 years limits the immediate consequences of this input[81], but it is also likely to make its impact on the deep-sea more permanent. Due to relatively poor biodiversity of the deep-sea compared to coastal, the seaweed wouldn't degrade at a fast rate. One of the main risks identified is to witness a proliferation of living organisms feeding on the sunken seaweed leading through respiration to an impoverishment in oxygen, leading to hypoxia and severely damaging the deep-sea biodiversity[82].

Many specialists within the scientific community are concerned about potential environmental consequences of massive seaweed sinking which need to be further assessed, and, beyond this issue, one recently published paper considers "unethical" to sink seaweed that could be of valuable use[83]. Economically, it also makes sense to valorise seaweed and use the biomass for solving human needs for products. Several projects are planned or are currently operating seaweed processing to **produce valuable products**, including food, feed, fertilisers, cosmetics, biofuels, biogas, cosmetics and polymers. These uses need to be further assessed by LCA taking into account both ecosystems preexistent to seaweed farms and carbon footprint of seaweed-based products on the whole value chain (cradle-to-cradle). Carbon storage in products is non-significant on a climatic point of view, as carbon is either quickly released back in the atmosphere when consumed (eaten, burned, etc.) or stored not long enough to be considered as sequestered (seaweed-based polymers or other lasting (e.g., building) materials only reach 25 to 30 years). These products are able to effectively reduce GHG emissions only if they emit significantly less GHG than currently used products, and if a substitution from these products actually happen. The substitution effect is variable depending on the products.

The mitigation impact of seaweed-based food thanks to its substitution to more carbon-intensive food such as meat is still to be fully proved. It is especially uncertain due to its dependency on consumer choice, the substitution effect being potentially limited. Further research is also needed to compare the carbon footprint of seaweed-based food with other plant-based alternatives.

The use as **feed** suffers the same limit of low protein content, with the advantage for diet changes to be more flexible. Planned use includes fish feed production for aquaculture as well as terrestrial farmed animals. The diversity of seaweed species could also provide indirect emissions mitigation when used as feed. For example, in vitro experiments have shown that adding small proportion of algae in ruminant feed could potentially reduce the farmed animal's methane emissions[84]. Seaweed-based **polymers**, at this stage of development, offer much lower performance than their fossil-based alternatives, with a high vulnerability to water[85]. But some examples are already on the market – like seaweed-based packaging replacing the fossil one[86]. Fertilisers, biofuels and biogas are recognised by experts as the seaweed-based products for which substitution is the most likely to occur. The use of

[80] Ibid.

[81] Ibid.

[82] Ibid.

[83] Ricart et al. *Sinking seaweed in the deep ocean for carbon neutrality is ahead of science and beyond the ethics*, 2022. [access: https://iopscience.iop.org/article/10.1088/1748-9326/ac82ff/pdf]

[84] Machado et al. *In Vitro Response of Rumen Microbiota to the Antimethanogenic Red Macroalga Asparagopsis taxiformis*, 2018. [access: https://pubmed.ncbi.nlm.nih.gov/29018917/]

[85] Ibid.

86 Notpla, "Products", December 2022. [access: https://www.notpla.com/products/]

seaweed-based **fertilisers** (including compost, liquid fertiliser, biochar) offers the advantage to potentially sequester part of the seaweed carbon in the soil organic carbon. However, better knowledge is needed to quantify their carbon balance comparing to conventional alternatives. The production of biochar uses significant amounts of energy which need to be compared with the net carbon sequestration from seaweed (who must itself be compared to the preexistent coastal ecosystems). It is to be noted that projects planning the production of biochar such as *Seaweed Carbon Solutions* (a Norwegian project bringing together SINTEF, DNV, Equinor and Aker BP) plan to couple it with carbon capture and storage (CCS)[87], which is **likely to witness that seaweed-based biochar production without CCS is a net emitter of GHG**. Production of **biofuels and biogas** from seaweed biomass has been an object of many scientific studies highlighting their potential. . Pilot projects have even led to small scale biofuel productions, such as Horizon 2020 MacroFuels project, which produced 20 liters of biofuel used by a test car for an 80 km drive[88]. Existing assessments com[89]paring seaweed-based biofuels to other biofuels conclude that the advantages of seaweed in terms of environmental, social and economic benefits override the technical disadvantages which is mainly its high content of inorganic matter[90]. If the quantity of carbon potentially stored in **cosmetics** is limited, these products are interesting for the seaweed's economic valorisation. Some projects also include the production of seaweed-based **textile fiber**[91], which has the advantage of being a long-lasting product. It is to be noted that not every seaweed can be processed to produce any of these products. Among the best performing species, sargassum in particular is unfit for food and feed and needs additional processing for fertiliser use due to its high concentration in arsenic[92].

[87] DNV (Det Norske Veritas). "Commencing carbon capture with seaweed", July 2022. [access: https://www.dnv.com/news/commencing-carbon-capture-with-seaweed-228139]

[88] Macrofuels. "Macrofuels in numbers", 2019. [access: https://www.macrofuels.eu/]

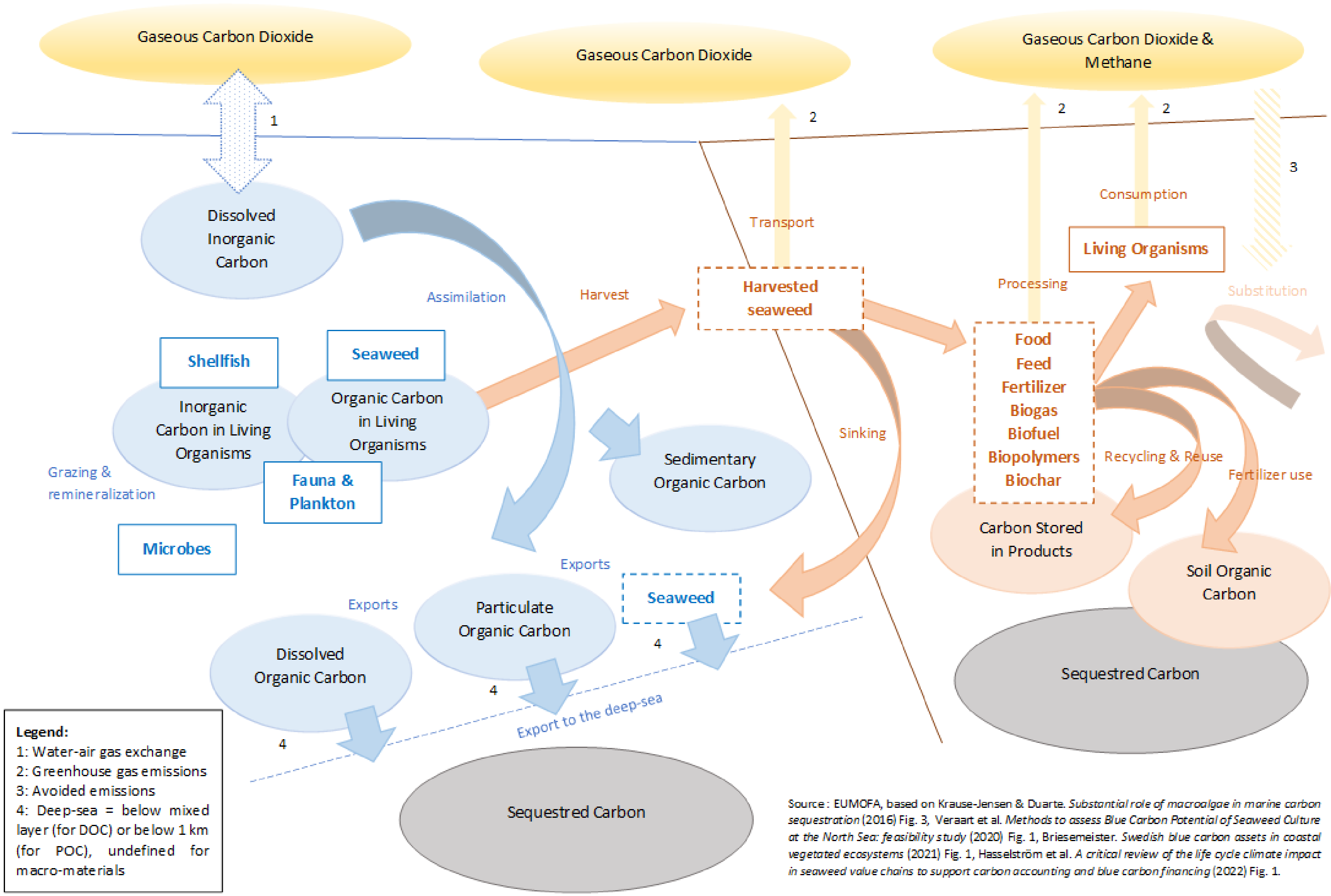
[89]

[90] Vassilev et al. *Composition, properties and challenges of algae biomass for biofuel application: An overview*, October 2016. [access: https://www.sciencedirect.com/science/article/abs/pii/S001623611630271X]

[91] Kelp Blue. "About", official website. [access: https://kelp.blue/about/]

[92] Interviews.

Figure 3.6: Marine seaweed carbon cycles



Source: EUMOFA, based on Krause-Jensen & Duarte. *Substantial role of macroalgae in marine carbon sequestration* (2016) Fig. 3, Veraart et al. *Methods to assess Blue Carbon Potential of Seaweed Culture at the North Sea: feasibility study* (2020) Fig. 1, Briesemeister. *Swedish blue carbon assets in coastal vegetated ecosystems* (2021) Fig. 1, Hasselström et al. *A critical review of the life cycle climate impact in seaweed value chains to support carbon accounting and blue carbon financing* (2022) Fig. 1.

3.5 Potential and barriers for using seaweed as blue carbon solution in the European Union

3.5.1 Potential to use seaweed ecosystems and productions as a blue carbon solution

According to the 2022 *Global seaweed productivity* article, seaweed net primary production is strongly coupled to climatic variables, and, all seaweed species considered together, is optimal at **temperate latitudes**[93]. Europe already hosts significant **seaweed ecosystems**, including kelp forests, which count among the best performing in terms of net primary production, and algal beds. Europe also benefits from large areas of the North Sea and Baltic Sea with significant **rocky substrates**[94]. According to a recent European Environmental Agency's report[95], some European coastal areas such as the German and Danish North Sea coasts, as well as the Baltic Sea (notably the Gulf of Finland) and the Bulgarian Black Sea coast suffer **eutrophication** (significant surplus of nutrients), making them potentially ideal location for seaweed farming or afforestation. This situation gives a significant possibility of acting on seaweed ecosystem conservation and restoration, as well as potential room for seaweed farming.

European geographical potential is not limited to continental Europe; **EU Member State's oversea territories** and their adjacent exclusive economic zones potentially provide additional areas for seaweed conservation and restoration, as well as potential areas for seaweed farming, particularly in the case of open-sea projects. Among the best performing seaweed ecosystems, sargassum are native from the subtropical Atlantic and could be potentially farmed. Among the other advantages of overseas territories, Azores and Canary Islands benefit from the nutrient-rich Canary Current, making it potentially easier to farm seaweed far from the coasts. It is also to be noted that the use of seaweed for carbon sequestration or storage in products is not limited to farmed seaweed. Sargassum blooms occurring in the Caribbean already provide significant amount of organic matter. *SOS Carbon* did exploit this phenomenon by conceiving easily scalable wild sargassum collection modules, with the plan to valorise these temporary surpluses for the production of liquid compost, fertilisers, cosmetics and biogas[96]. At a smaller scale, similar projects could also be led to exploit existing *Ulva* blooms in continental Europe.

Another asset for the European Union to develop seaweed large scale farming and processing is its significant **industrial infrastructure**, with leading global companies in the sector of fertilisers (Yara), in the petrochemical industry (BASF, LyondellBasell) and in oil & gas (TotalEnergies, Eni) showing growing interest for biobased alternatives to fossil fuels. This industrial basis, facing both pressure for decarbonisation from public climate policies and supply issues for fossil fuel procurement, is significant both in terms of its R&D capacities and its ability to scale-up projects. For processing solutions of low technology readiness level to be explored, the EU can count on a powerful tool to support innovation with the Horizon Europe research program. European projects for processing seaweed have been benefitting from public support thanks to this tool since several years (Kelp EU, GENIALG). This support for applied research can also count on leading research institutions in marine science.

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93 Pessarrodona et al. *Global seaweed productivity*, September 2022. [access: https://www.science.org/doi/10.1126/sciadv.abn2465]

94 Duarte et al. *Global estimates of the extent and production of macroalgal forests*, 2022. [access: https://onlinelibrary.wiley.com/doi/10.1111/geb.13515]

95 European Environmental Agency. *Nutrient enrichment and eutrophication in Europe's seas*, 2019. [access: https://www.eea.europa.eu/publications/nutrient-enrichment-and-eutrophication-in]

96 SOS Carbon. "Our work", official website. [access: https://soscarbon.com/our-work]

3.5.2 Barriers and challenges

The main challenge to use seaweed as a blue carbon solution is the **technical challenge of effectively quantifying carbon sequestration** from seaweed ecosystems. As previously explained, most of the estimated carbon sequestration from wild seaweed occurs thanks to carbon exports to the deep-sea. It is therefore impossible to base carbon accounting on sediments sampling on the contrary to other blue carbon ecosystems. The current state of the art is able to witness significant exports of macroalgae material and dissolved organic carbon to the deep-sea. Quantification is based on theoretical modelling on the global level, with significant ranges of uncertainty. Carbon net primary production and to a greater extend sequestration from given seaweed ecosystems closely depends on the type of ecosystem and the local environmental factors, making it even more difficult to quantify carbon sequestration level on the local level. Quantification of carbon and oxygen fluxes is possible in low depth coastal areas, but such monitoring (AEC, benthic chambers coupled with sensors) is costly and only gives an estimation of the net primary production. Such estimations are not sufficient to precisely quantify carbon sequestration from a given wild seaweed ecosystem. They can be useful to provide an estimation of carbon sequestration from a seaweed farm, only if led both before and during the project (net sea-use change), and if completed by life cycle assessments on the use of the harvested seaweed. Such monitoring technologies cannot be used in the open-sea or in deep-sea environments where monitoring must rely on a pH and oxygen sensors as well as observation from remotely operated vehicles, at the expense of the precision. The Ocean 2050's project to quantify carbon sequestration from farms based both on sediment samples and estimations of exports[97] could provide interesting information, even if its focus on existing farming activities limits the opportunity to compare these situations with preexisting ecosystems.

Another major challenge is the **space, light and nutrient availability** needed for seaweed farming projects. As mentioned above, space in European coastal areas is already very constrained by various uses and by the presence of other ecosystems. Given the uncertainty of carbon sequestration from seaweed, the risk of replacing better performing ecosystems is significant. Open-sea projects are less constrained by space and light availability, they are limited by the low nutrient concentration. The EU doesn't benefit from any of the major upwelling current, except in the oversea territories of Azores and Canary Islands. Unless open-sea projects are situated on these strategic locations, artificial upwelling technologies are likely to be needed to concentrate the nutrients for the seaweed growth in an open-sea environment where their concentration is naturally low[98]. The impact of such technologies on the deep-sea environment is still uncertain and could potentially impact phytoplankton and fish stock renewal. Open-sea projects are also legally limited to the countries' exclusive economic zones[99].

The risks of large-scale seaweed farming for existing ecosystems are not limited to the ecosystems' competition for space, light and nutrient. The high resilience and adaptability of seaweed ecosystems makes it likely to become invasive when allogenous to the farm's environment. This risk is especially striking in the Mediterranean, where highly valuable (for biodiversity as well as carbon sequestration) *Posidonia* seagrass ecosystems have been severely damaged by an invasion from the *Caulerpa taxifolia* seaweed. All experts interviewed agree on this risk and on the fact that seaweed farming must exclusively conducted with species native to the farm's environment.

A major limit is Europe lacking the existing **economical and logistical infrastructure** to develop seaweed large scale farming, transport, processing and distribution, as well as the corresponding markets. Given the current state of play of seaweed farming in the world, with the EU accounting for

[97] Interviews.

[98] Ibid.

[99] Ibid.

around 0,5% of the global farmed seaweed production[100][101], the implementation of funding mechanisms producing blue carbon credits from seaweed production would for its vast majority finance seaweed production in Asia, whose countries can count on existing infrastructures and markets. Most of current projects applying carbon accounting techniques to seaweed farming are already focusing on existing farms with significant production volumes, which are almost exclusively located in Asian countries[102]. There could be an additional risk of setting international standards based on existing practices potentially less adapted to the European context. In addition to the worry that an EU-led initiative to move toward seaweed blue carbon credits is more likely to lead to benefit to other countries, those credits could potentially disrupt these existing markets, creating incentives for new uses of seaweed whose substitution potential is uncertain at the expense of well-established uses.

3.6 Conclusions and recommendations

3.6.1 Main conclusions

This overview of scientific knowledge on carbon storage and sequestration from seaweed ecosystems in the natural environment, as well as seaweed human-led seaweed production (harvesting and farming), together with the characteristics proper to Europe and especially the European Union, leads to the following conclusions:

- Science is not robust enough for blue carbon credits to be extended to seaweed ecosystems and seaweed farming. If carbon accounting is not precise enough to quantify the tons of carbon sequestrated from seaweed ecosystem conservation or restoration or from seaweed farming, a growing number of publications is witnessing the reality of significant carbon exports to the deep-sea from seaweed coastal ecosystems. The majority of scientific articles also agree on the climate change mitigation effect of seaweed ecosystems globally, and the science is able to identify the best performing ecosystems in terms of net carbon intake (NPP).
- Given the significant role of seaweed ecosystems in marine carbon cycles, the existing significant estimations of net primary production and carbon sequestration from seaweed worldwide, and the IPCC report's conclusions on the central role of oceans in global climate regulation, seaweed ecosystems are significant enough to deserve careful attention from European climate and environmental policies.
- Possible actions to integrate seaweed ecosystems in climate policies include seaweed conservation, seaweed restoration and seaweed farming. These actions are potentially able to provide both climate change mitigation and environmental benefits. Conservation and restoration are the options with lower risks to prove counterproductive. Given the numerous uncertainties on the impacts of large-scale seaweed farming on climate and on the environment, if this option has to be implemented it must be strictly framed and progressively scaled-up.
- The EU hosts significant wild seaweed ecosystems but only accounts for an unsignificant fraction of the global human-led seaweed production, especially with regards to the Asian countries' production levels. If large scale seaweed farming has to be developed as a tool to fight climate change, it is more likely and more relevant to be developed outside Europe, in countries with highest potential of scaling-up, and where both the environment and the market are already adapted to these productions.

[100] FAO, 2019.

[101] Araújo et al. *Current Status of the Algae Production Industry in Europe: An Emerging Sector of the Blue Bioeconomy*, January 2021. [access: https://www.frontiersin.org/articles/10.3389/fmars.2020.626389/full]

[102] Interviews.

3.6.2 Need for public policies to address the knowledge gaps in seaweed ecosystem carbon sequestration capacities

This chapter witnesses more the significant knowledge gaps on seaweed ecosystems' potential of carbon storage and sequestration than their significant potential. It also highlights the need for better knowledge of the environmental conditions of European coasts and basins, as a necessary first step before implementing projects disrupting natural biological and chemical cycles. For the EU to take the best of seaweed climate change mitigation potential and environmental co-benefits, the following recommendations can be made:

- Assessing carbon net primary production occurring thanks to existing wild seaweed ecosystems, addressing the knowledge gap between an ecosystem's net primary production and its contribution to carbon sequestration and estimate as much as possible exports to the deep-sea leading to carbon sequestration (macromaterial, POC and DOC). Identifying the most productive and the most endangered ecosystems. These assessments can be carried on EU MSP basins, potentially including non-EU neighboring countries[103], and in Member States' oversea territories. The relevant ecosystems are likely to be kelp forests and algal beds in continental Europe, sargassum forests, algal turfs and coralline beds in the oversea territories. These assessments should ideally also assess the role of these ecosystems in other biochemical cycles and their impact on biodiversity, as well as their degradation due to human activities.
- Assessing the environmental conditions of European coastal areas and basins, with special regard to nutrient availability and eutrophication levels. According to the recent *Nutrient enrichment and eutrophication in Europe's seas* report from the European Environmental Agency, significant knowledge gaps exist, notably for the Atlantic coast and the Mediterranean[104]. Additional assessment must be carried out in areas suffering from eutrophication to identify the opportunity to lead pilot seaweed farming projects able to deliver on both climate change mitigation and on environmental restoration. Involving as much as possible coastal communities to identify in the potential economic and societal co-benefit from new seaweed ecosystems and the opportunity for scaling-up.
- Further supporting research on life cycle assessment of seaweed-based products from existing farms and from new farms for which a carbon flux and carbon sequestration assessment have to be led on the preexisting ecosystem. Ideally, life cycle assessment must take into account the sea-use change due to farming activity and the seaweed harvest, transport, processing, use, end-of-use and potential recycling (cradle-to-cradle). Identifying the seaweed-based products with the lowest carbon footprint compared with their fossil-fuel based alternative, and the potential for substitution. For the case of feed, further investigating the potential to reduce methane emissions from animals thanks to seaweed-based additives.

3.6.3 Needs for public policies to support the best use of seaweed for climate change mitigation purposes

Given the remaining gaps in scientific knowledge, the need for public policies using seaweed ecosystems for climate change mitigation purposes will mainly depend on the finding of further research. However, some policy measures with low potential of counterproductive effects and

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[103] The existing *Nordic Blue Carbon* and *AFRIMED* projects can be identified as examples of cooperation with non-EU countries on seaweed ecosystems, respectively in the North Sea/North Atlantic and in the Mediterranean.

[104] European Environmental Agency. *Nutrient enrichment and eutrophication in Europe's seas*, 2019. [access: https://www.eea.europa.eu/publications/nutrient-enrichment-and-eutrophication-in]

presenting significant co-benefits along with their potential climate change mitigation impact can be identified:

- Taking action to preserve the most endangered seaweed ecosystems and the ecosystems with the best carbon sequestration potential, such as kelp forests. Among the main political levies, European and national policies can act on the control of invasive species and the reduction of eutrophication. Given the relative resilience of seaweeds compared to other coastal ecosystems, conservation policies benefitting to more than just seaweed ecosystems could be prioritised. The effort on seaweed protection must not be detrimental to other more fragile and also environmentally valuable ecosystems such as seagrass.
- Supporting initiatives for seaweed ecosystem restoration where they are the most degraded and when the potential for recovery is significant. Restoration of ecosystems can be led in cooperation with non-EU neighboring countries sharing the same sea basins, as it is the case for *Cystoseira* ecosystems restoration efforts in the Mediterranean.
- Supporting pilot projects of seaweed farming in areas suffering environmental degradation from eutrophication, within the double objective of GHG mitigation and environmental restoration. Conditioning the scaling-up projects to a constant monitoring of net carbon intake, environmental conditions and as much as possible carbon sequestration. Identifying and using potential synergies with the water framework and the marine strategy framework directives. Such projects can possibly be coupled with multitrophic aquaculture.
- Supporting the development of seaweed processing to supply products (e.g. food, feed etc) and seaweed-based substitutes to existing fossil-fuel based products. For the latter, focus in particular on fertilisers, biofuels and biogas.
- Considering supporting open-sea pilot farming projects in economic exclusive areas of Member State's oversea territories benefitting from natural upwelling. Exploring the logistical and economical possibility of on-site processing.
- Seaweed sinking for carbon sequestration purposes so far has no proof of positive environmental, climate or economic benefits. Hence, in the present state of knowledge, it should not be considered as a valid policy option.

4 HOW SEAWEED CAN TRANSFORM REGIONAL ECONOMIES

*Chapter authored by Antoine Erwes and Nicolas Erwes

4.1 Introduction

The new seaweed (macroalgae) economy is expected to provide climate resilience while stewarding ecosystems through regenerative practices that enrich both natural habitats and local communities. It is presented as the ideal regenerative material that can be used in a myriad of innovative and sustainable product applications, support economic growth, and reinforce the resilience of coastal communities. Yet there is a growing demand for seaweed products that growers and harvesters cannot fulfill. Seaweed farms around the world, but in Europe more specifically, struggle to sustainably scale their operations due to a variety of factors (knowledge silos, lack of data transparency, unpredictable production cycles, inefficient supply chains, complex regulatory frameworks), all of which disincentivise risk averse investors and businesses. Concerns have also been raised over the actual "hype" around seaweed, and more specifically its carbon sequestration potential. Demand for quality, sustainable products is high, and multinationals are eager to meet their sustainability goals with seaweed products. The scalability of the European seaweed industry rests on improved transparency and informational flows will facilitate impactful investments and accelerate the implementation of business models more aligned with the socio-economic resilience of coastal communities. Thus, this study sets out to identify the best practices within the European Union (EU)'s seaweed value chain and understand how these strengths can further be leveraged to sustainably scale regional seaweed production. After providing a brief overview of the state of the European seaweed industry, this report will investigate the best economic, social, environmental, and policy practices relating to seaweed within the EU, and conclude with several recommendations on the immediate and long-term steps required to support the sector's growth.

4.2 Overview of the European seaweed industry

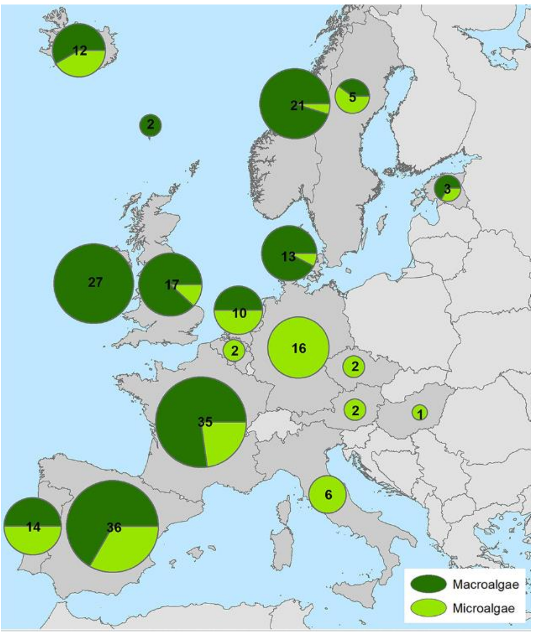
The European seaweed industry is both small in scale and regionally imbalanced. Although the first recorded use of seaweed in Europe dates back to the 17th century when it was used for the production of glass in France and Norway, the industry is dwarfed by Asia. According to the latest data from the United Nations Food and Agriculture Organisation (FAO), Europe (EU, Norway, and United Kingdom) total seaweed production in 2019 hovered below 300 000 tons, a level which was last reached in 2000.[1] This represents less than 1% of total global production.[2] Araujo et al.'s study found that about 180 companies encompassed Europe's seaweed production sites, and appear to be evenly distributed geographically speaking.[3]

[1] Food and Agriculture Organization (FAO), "Seaweeds and microalgae: an overview for unlocking their potential in global aquaculture development", (Rome, 2013), https://www.fao.org/3/cb5670en/cb5670en.pdf, 4.

[2] FAO, "Seaweeds and microalgae", 4.

[3] Rita Araujo, Fatima Calderon, Javier Lopez, Isabel Azevedo, Annette Bruhn, Silvia Fluch, Manuel Tasende, Fatemeh Ghaderiadakani, Tanel Ilmjarv, Martial Laurans, Michael Monagail, Silvio Mangini, César Peteiro, Celine Rebours, Tryggvi Steffanson, and Jorg Ullmann, "Current Status of the Algal Production Industry in Europe: An emerging Sector of the Blue Economy", *Frontiers in Marine Science,* (27 January 2021), https://www.frontiersin.org/articles/10.3389/fmars.2020.626389/full

Figure 4.1: Number of companies producing algae in Europe



Source: Araujo et al, "Current Status of the Algal Production Industry in Europe: An emerging Sector of the Blue Economy"

Yet the production statistics clearly show that three countries concentrate the majority of this production, Norway (58%), France (17%), and Ireland (10%).[4] This discrepancy between number of companies and actual production levels highlights the structural and geographical imbalance of the European seaweed industry. Most companies are young and lack the experience held by the traditional regions in Norway, Britany (France), and Ireland. 55% of the companies sampled in a study by the business organisation Seaweed For Europe were created less than 10 years ago, and nearly 60% had fewer than 10 employees.[5] Indeed, most of the "new players" have just begun implementing aquaculture facilities or are in the process of conducting pilot trials.

One final characteristic of Europe's seaweed industry, which hampers its scalability, is that wild harvesting accounts for nearly 99% of total production.[6] The main difference lies in the way it is harvested: countries with a stronger seaweed economy, namely Norway, France, and Ireland, have increasingly turned towards mechanical harvesting to increase yields (with technologies adapted to the cultural habits of each coastal region), whereas other countries still resort to manual harvesting (or even diving like in Portugal).[7] Yet wild harvesting is not compatible with the growing demand for seaweed: yields have decreased due to excessive harvesting and unpredictable weather patterns in the

[4] FAO, "Seaweeds and microalgae", 4.

[5] Seaweed for Europe, "Investor Memo: The Case For Seaweed Investment in Europe", (16 October 2021),https://www.seaweedeurope.com/wp-content/uploads/2021/10/S4E-InvestorMemo-MainReport-16OCTOBER2021.pdf, 23.

[6] North Sea Farmers, "Market potential report for cultivated seaweeds in existing seaweed food markets", report for Interreg 2 seas ValgOrize project, (January 2021), https://www.northseafarmers.org/news/2021/Seaweed-market-study_210302.pdf, 25.

[7] NETLAGAE, "Seaweed Industry in Europe", (October 2012), https://www.seaweed.ie/irish_seaweed_contacts/doc/Filieres_12p_UK.pdf, 5.

past years.[8] Not to mention that the environmental impact of scaling these operations is uncertain and likely to deplete European natural stocks.[9]

4.3 Economic best practices

Three main practices have been implemented across the EU to stimulate the economic potential of seaweed: building seaweed networks, creating synergies with other blue economy sectors, and technological innovation.

a. Seaweed "networks" and hubs

The first practice revolves around the creation of seaweed networks, focused on linking upstreaming and downstream activities. The objective is to create a "hub" in which all regional stakeholders are able to communicate and conduct business. The French region of Britany has spearheaded such efforts. Regional and local buyers are able to directly interact with seaweed farmers. Networks such as "Merci Les Algues" increase the negotiating power of seaweed producers and help ensure that the creation of wealth benefits coastal communities. This is achieved by working with local agrifood businesses to build standards designed to raise awareness about the benefits of seaweed and encourage its down-stream applications in the value chain. A more macroscopic example of such networks is the EU's Genialg project. It was the first industry-driven network designed to boost the seaweed industry by pooling the knowledge and expertise of biorefineries, seaweed producers, and geneticists. This initiative is important in bridging knowledge gaps in supply chain management and seaweed business management, both of which are crucial in helping to scale the seaweed industry in Europe.[10]

Another form of seaweed network which has rapidly emerged in Europe are incubators. This practice is most visible in Belgium and the Netherlands, where universities have developed "seaweed" focused incubators. Researchers and students are encouraged to develop innovative ideas and technologies in a safe environment, supported with institutional research resources and funding.[11] Incubators are supposed to help bridge knowledge gaps between academic research and industry needs, and in doing so create a new ecosystem of innovative startups and projects from which the seaweed industry can grow. The growing interest for seaweed across Europe however has also pushed traditional accelerators to support seaweed related projects. According to the market researcher "Phyconomy", 24 seaweed startups have joined accelerators in autumn 2021.[12] These accelerators are adding seaweed projects to their pipelines with the hopes of linking them with other blue economy projects and building a regional ecosystem of ocean solutions that directly address global challenges such as climate change and food security.

One of the unintended consequences of these seaweed networks, especially those concentrating at the regional level, is to amplify the regional inequalities. Indeed, most of the seaweed industry is now concentrated in the region of Britany, with other maritime regions struggling to develop their own local seaweed networks because downstream stakeholders prefer to work with the more mature networks

[8] Dutch Ministry of Foreign Affairs, Centre for the Promotion of Imports from Developing Countries, "The European market potential for seaweed", last updated 14 February 2022, https://www.cbi.eu/market-information/fish-seafood/seaweed/market-potential

[9] Michelle Carrere, "Why your kelp-based products could be bad news for biodiversity", World Economic Forum (WEF) (April 27, 2021), https://www.weforum.org/agenda/2021/04/how-increased-kelp-farming-could-effect-marine-biodiversity/

[10] GENIALG, "GENIALG project results help to boost the European Seaweed Sector", (August 19, 2021), https://genialgproject.eu/2021/08/19/genialg-project-results-help-to-boost-the-european-seaweed-sector/

[11] Jessica Knoop, "A new crop in the sea: Seaweed cultivation in Belgian waters", Phycology research group of the University of Ghent, accessed on December 12, 2021, http://bluegent.ugent.be/new-crop-sea-seaweed-cultivation-belgian-waters

[12] Steve Hermans, "24 seaweed startups in 2021 autumn accelerator cohorts", (October 16, 2021), https://phyconomy.net/articles/18-seaweed-startups-in-2021-autumn-accelerator-cohorts/

and infrastructure of Britany.[13] Moreover, most incubators and accelerators tend to focus on research-intensive projects and, for the time being, offer few applications centered on the needs of the industry.

b. Synergies with other blue economy activities

The second practice concerns the creation of synergies with other blue economy activities. The implementation of the Maritime Spatial Planning (MSP) Directive and other related policies across Europe has pushed many businesses and governments to appreciate the added-value of creating links with other industries. In Britany for example, seaweed and oyster aquaculture experts have taken into account the mutual reinforcing effect that these two bioresources have on each other. Seaweed helps to protect oysters against eutrophication and rising water acidity, and the oysters release minerals and other nutrients beneficial for the growth of seaweed.[14] This method, known as Integrated Multi-Trophic Aquaculture (IMTA), is beneficial for farmers in a variety of ways: increased yields, diversification of revenue streams, stability of revenues throughout the year, and ecosystem services which improve the resilience of coastal communities to climate change.

Creating synergies can also have profound strategic implications. In the Danish autonomous region of Greenland, the “Nordplus” network was created to help connect the local seaweed industry with other blue economy networks. The objective was to pool scarce resources and optimise the use of infrastructure, labour, and investments.[15] Similar initiatives, which received EU funding, also exist in Belgium and the Netherlands, are spearheading European efforts to valorise offshore infrastructure to scale seaweed cultivation. Wier and Wind (Interreg funding), UNITED (H2020 funding), and OLAMUR (Horizon Europe funding), are examples of projects working on the sustainable and efficient optimisation of marine resources. The Dutch project under the leadership of Wageningen Marine Research is investigating how to implement automated seaweed farming between offshore installations.[16] The region of Britany and Pays de la Loire in France has also built the largest wind farm parks in the country, and some seaweed cultivators based in Britany are working with local authorities to see how seaweed cultivation attached to these offshore infrastructures.[17]

Creating synergies between different blue economy sectors has two direct advantages: first, it allows for a more efficient use of existing infrastructure, and seaweed farmers have access to processing facilities which can be used in other aquaculture sectors.[18] Second, it reinforces the stability of blue economy employment in these regions. Processors are able to work with different aquaculture producers and producers are able to spread out their revenues throughout the year by working with different bioresources. Important governance issues remain to be solved however, including inconsistencies between different sectoral regulations, the lack of long-term spatial planning, and uncoordinated maritime policies to name a few.[19]

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[13] Interview with local municipality in Britany, June 21 2021

[14] Fabrice Rousselot, “Huîtres et algues : partenaires pour le meilleur et pour le pire dans un océan en mutation”, *The Conversation* (8 February 2022), https://theconversation.com/huitres-et-algues-partenaires-pour-le-meilleur-et-pour-le-pire-dans-un-ocean-en-mutation-176322

[15] Nordplus, “Seaweed is turning into food and networking”, accessed 2 December 2022, https://www.nordplusonline.org/project_articles/seaweed-is-turning-into-food-and-networking/

[16] Wageningen, “Seaweed underneath the wind turbines”, accessed 2 December 2022, https://www.wur.nl/en/show-longread/seaweed-underneath-the-wind-turbines.html

[17] Interview with local seaweed producer in Britany, June 21 2021.

[18] H.M. Jansen, L Tonk, A Werf, I Meer, S van Tuinen, S Burg, J Veen, L Bronswijk, and E Brouwers, "Development of offshore seaweed cultivation: food safety, cultivation, ecology, and economy", *Wageningen University and Research Report C012/19* (2018), https://edepot.wur.nl/470706

[19] European Commission, European Climate, Infrastructure and Environment Agency, “Best Practice Guidance in Multi-Use Issues and Licensing Procedures”, (June 2021), https://maritime-spatial-planning.ec.europa.eu/sites/default/files/best_practice_guidance_in_multi-use_issues_and_licensing_procedures.pdf, 15.

c. Technological innovation

The last practice designed to reinforce the economic potential of seaweed concerns is the focus on technological innovations to help scale seaweed production at a lower cost. One key example is the AlgaeDemo project, supported and funded by the European Maritime Fisheries and Aquaculture Fund. The project is developing autonomous harvesting vehicles to monitor seaweed growth in order "to reduce costs, the risks to people and property, and contribute to a healthier ocean."[20] These sensors continually capture and transmit live data, thus enabling farmers to directly assess the growth patterns of their seaweed crops without having to go out to sea. A similar project in Norway called Soft Seaweed is focusing on helping seaweed farmers with their reporting by developing a centralised software that processes and stores all key data [21]. Finally, a recent initiative called KELP EU is supporting seaweed projects by building tailored processing plants across Europe [22]. The objective is to enable the EU to tackle food security by providing high-quality food and ingredients. KELP EU seeks to build the EU's processing capabilities by financially supporting mature technologies (TR 6 to 8) to enter the market.

Notwithstanding the reliability and burdensome financial cost of these technologies, it is important to note however that the challenges facing the European seaweed industry are not technology driven but more related to governance and market issues. Moreover, seaweed has always been a rural activity essential for the livelihoods of coastal communities. Many lessons can be learned from the agricultural sector in that regard: yields have increased, but rural communities are declining and the wealth generated does not benefit the remaining communities. The overuse of technology in the seaweed industry could therefore discriminate unskilled labour in coastal communities and reduce the socio-economic externalities of this bioresource.[23]

4.4 Social

Seaweed is more than a simple crop and plays a fundamental role in shaping the livelihoods of coastal communities. From a marketing perspective, producers also understand that it is pivotal to engage the public and raise awareness about the added value of seaweed in their everyday lives. There multiple forms of initiatives seeking to harness the social role of seaweed across Europe.

a. "Seaweed" events and platforms

Various events directly or indirectly addressing seaweed have emerged over the past decade. The biggest event is the EU-led Seagriculture, which unites seaweed specialists from all levels of the value chain to address specific scientific discoveries and discuss how they can be transferred into the market.[24] The European Algae Biomass Association's event "AlgaEurope" is another example of a large conference focused on creating synergies between scientists, industries, and decision makers in order to accelerate the development of the seaweed sector in Europe [25]. Some organisations have developed partnerships to increase the impact of their events. This is the case of the Monaco Blue Initiative and Seaweed For Europe, which hosted a multistakeholder event to define the role of seaweed in solving

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[20] European Commission, Directorate General for Maritime Affairs and Fisheries, "ALGAEDEMO demonstrates full potential of seaweed", (25 October 2022), https://oceans-and-fisheries.ec.europa.eu/news/algaedemo-demonstrates-full-potential-seaweed-2022-10-25_en

[21] Softseaweed, "About", accessed 2 December 2022, https://softseaweed.com/

[22] European Commission, Directorate General for Maritime Affairs and Fisheries, "KELP-EU: "KELPING THE EU", (31 March 2022), https://oceans-and-fisheries.ec.europa.eu/news/kelp-eu-kelping-eu-2022-03-31_en

[23] Tillin Wilding, H Corrigan, SE Stuart, E Ashton, I Felstead, P Lubelski, A Burrows, and M Smale, "Seaweed aquaculture and mechanical harvesting: an evidence review to support sustainable management", *Natural England Research Report NECR378*, (September 2021), https://www.mba.ac.uk/wp-content/uploads/2022/05/Wilding_et_al_2021_-NE_Seaweed-aquaculture-and-mechanical-harvesting.pdf, 5.

[24] Seagriculture, "About", accessed 2 December 2021, https://seagriculture.eu/

[25] Algaeurope, "About", accessed 2 December 2021, https://algaeurope.org/

global climate and health issues.[26] More business-centric events also exist, such as the BioMarine Business Convention, an international platform dedicated to innovation and investment in the blue bioeconomy.[27]

Most of the aforementioned events are primarily targeting professionals in the sector, occasionally extending their reach to newcomers seeking to develop new business opportunities. Yet local associations and non-profit organisations are also playing an important role in the promotion of seaweed to the general public across Europe. The Kelp Forest Foundation, Seaweed For Europe, the Norwegian Seaweed Association, and North Sea Farmers – to give a few examples – regularly host events to explain the potential of seaweed in Europe. Virtual events, such as "Seaweed Around the Clock", are also emerging and enabling people from all parts of the world to engage with seaweed professionals on specific themes related to the seaweed industry.[28] On a more local level, in Finland, the Aalto University has launched the "Seaweed Kitchen" to teach people how to cook with seaweed through immersive experiences.[29] Chefs in France, Spain, Belgium[30], and the Netherlands are now revisiting traditional dishes by integrating seaweed into the ingredients. For example, during Season 12, episode 15 of French Top Chef, candidates were asked to use Ulva and Wakame as central parts of their dish.[31] The EU has also launched the #TasteTheOcean campaign with celebrity chefs all over Europe to encourage consumers to buy and enjoy sustainable fish and seafood.

Various online tools have also been developed to raise awareness about the seaweed industry. The recently launched EU4Algae platform for instance, is focused on identifying and promoting European best practices for the production of seaweed.[32] Other networks such as Seaweed For Europe and the SubMariner network are working on supporting local businesses by identifying the best partners to scale their operations.[33] Smaller projects, such as Phyconomy, Kelp Forest Foundation, and Seaweed First, are working on promoting seaweed to a wider audience through data transparency.

b. Partnerships with schools and other end-users

Most countries in Europe have begun to develop partnerships with schools to educate children about the potential of seaweed and raise awareness about its daily applications (from food security to climate change resilience). In France, elementary schools in Britany regularly go visit seaweed farms. The youth are therefore able to engage with seaweed producers and understand its genetic diversity, how it is produced, and its numerous socio-economic and environmental benefits.[34] Particular emphasis is placed on distinguishing the invasive green algae caused by the excessive use of fertilisers from the cultivated or harvest macroalgae. In the Netherlands for instance, farmers are targeting local communities as a whole (not just schools), showing to people how their work impacts their livelihoods and the natural ecosystems. Farms such as Kelp Blue regularly organise field trips, workshops, and interviews to help locals understand how this bioresource positively impacts their community.[35] In

[26] Monaco Ocean Week, "Seaweed Day", accessed 2 December 2022, https://www.monacooceanweek.org/wp-content/uploads/SeaWeed-flyer.pdf

[27] BioMarine, "About", accessed 2 December 2022, https://biomarine.org/

[28] Seaweed Around the Clock, "About", accessed 2 December 2022, https://seaweedaroundtheclock.vfairs.com/

[29] Aalta University, "Seaweed kitchen: future snacks workshop with children as part of the ClimATE events", (17 October 2019), https://www.aalto.fi/en/research-art/seaweed-kitchen-future-snacks-workshop-with-children-as-part-of-the-climate-events

[30] Donald Deschagt, "Le Homard et la Moule", accessed 2 December 2022, https://lehomardetlamoule.be/

[31] Emeline Collet, "Top Chef, saison 12, épisode 15 : cinquante nuances de vert", accessed 2 December 2022, https://www.leparisien.fr/culture-loisirs/tv/top-chef-saison-12-episode-15-cinquante-nuances-de-vert-19-05-2021-J34WA5VKQBG5VK24NBUZZ2BHZU.php

[32] European Commission, Maritime Forum, "EU4Algae", accessed 2 December 2022, https://webgate.ec.europa.eu/maritimeforum/en/frontpage/1727

[33] Seaweed for Europe, "About", accessed 2 December 2022, https://www.seaweedeurope.com/

[34] Ouest France, "Initiation à la cueillette d'algues par un alguiste", (26 May 2018), https://www.ouest-france.fr/pays-de-la-loire/piriac-sur-mer-44420/initiation-la-cueillette-d-algues-par-un-alguiste-5783855

[35] Interview done with Kelp Blue in Netherlands, May 13, 2022.

Greenland, the "Nordplus" programme enshrines seaweed cultivation and harvesting as an essential pillar of the local socio-economic tissue, with particular emphasis the cultural role and tradition of seaweed in Inuit culture.[36] Ireland's youth awareness raising campaigns have focused on the downstream value chain. The "Green Schools" initiative accompanies children in making their own "seaweed goo" to understand the role and uses of alginates.[37] At EU level, the EU Coalition for Ocean Literacy was launched to connect diverse organisations, projects, and people that contribute to ocean literacy and the sustainable management of the oceans.

c. Promoting gender equity

The seaweed industry is known for being a sector which empowers the role of women in coastal communities. This is specifically true in Africa and Asia where the majority of seaweed farmers are women. As a true outlier within the blue economy, various studies have studied the driving force of women within the seaweed industry and its positive impact on coastal communities (improved quality of life and reinforced social acceptance).[38] Few studies have documented the feminisation of the seaweed industry in Europe. The French organisation Pericles has focused on promoting the role of women within the seaweed industry in their recently released short documentary called "women and the sea in Britany: seaweed".[39] The objective was to encourage young entrepreneurs to join the sector by showing that more and more women were leading seaweed farms in Britany. To this effect, the French government showcased the biographies of 42 women working in the aquaculture sector[40] and published a report in 2017 to study the barriers preventing women from working in the French aquaculture sector.[41] At the European level, the Astral Project was launched in March 2022 as a networking event for women in aquaculture. The objective is to share experiences and build a network of women entrepreneurs looking to engage in the seaweed and aquaculture sectors.[42]

4.5 Environment

Seaweed plays a pivotal role in the management of coastal ecosystems and various projects across Europe have blossomed to better understand and improve these effects.

a. Reinforcing biodiversity

Many farms and projects across Europe have embraced seaweed's role as a key ecosystem service provider. A land-based project in Denmark called Pure Algae is planning to use seaweed farming to filter waste water emanating from fish aquaculture and other blue economy activities which release excess nutrients into the oceans.[43] The integrated seaweed farms will therefore help to purify nutrient

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[36] Nordplus, "Seaweed is turning into food and networking", https://www.nordplusonline.org/project_articles/seaweed-is-turning-into-food-and-networking/

[37] Green Schools Ireland, "Make your own... seaweed goo!", accessed 2 December 2022, https://greenschoolsireland.org/resources/make-your-own-seaweed-goo/

[38] Flower Msuya and Anicia Hurtado, "The role of women in seaweed aquaculture in the Western Indian Ocean and South-east Asia", *European Journal of Phycology* 52:4, (10 October 2017, https://www.tandfonline.com/doi/pdf/10.1080/09670262.2017.1357084

[39] PERICLES, "Women and the sea", accessed 2 December 2022, https://www.pericles-heritage.eu/women-and-the-sea-in-brittany/

[40] Michèle Villemur, "Femmes de mer : 42 portraits", (July 2017), http://www.ressources-marines.gov.pf/wp-content/uploads/sites/24/2017/07/femmes-de-mer-42-portraits-2015.pdf

[41] Marie Christine Monfort, Pascale Baelde, and Claudy Vouhe, "La place des femmes dans les secteurs pêche et aquaculture en France", *Franceagrimer* (July 2017), https://www.franceagrimer.fr/fam/content/download/54468/document/Rapport%20Final%20Place%20des%20femmes%20FAM%2013072017%20%28002%29.pdf?version=7

[42] Astral, "Astral all-Atlantic 2021 Pledge", accessed 2 December 2022, https://www.astral-project.eu/news/astral-all-atlantic-pledge

[43] Pure Algae, "About", accessed 2 December 2022, https://www.purealgae.dk/

rich waters while also produced high-quality seaweed. This "restorative aquaculture" model builds on the concepts of IMTA and is one of the key priorities of the Danish government which is seeking to address the eutrophication of the Baltic Sea. Similar IMTA projects can be found in Britany (Algolesko)[44], Belgium (Colruyt)[45] and Portugal (Aquaponics Portugal).[46] Algolesko for instance, is working in a Natura 2000 area in order to assess how seaweed-led IMTA can be beneficial to other aquaculture activities in the region. As mentioned previously, several studies have voiced their concerns with the strong European reliance on natural seaweed stocks, which may possibly result in the disturbance of marine ecosystems.[47] Various projects have emerged to address this environmental need. Kelp Blue is working with Nature Metrics to assess the biodiversity impact of seaweed farming on marine ecosystems.[48] The Dutch company Hortimare is focusing on the development of reliable genetic pools for seedlings, a crucial step in preserving the integrity of seaweed ecosystems.[49] The company argues that the scalability of the European seaweed industry requires high-quality seeds in order to provide stable yields. Finally, another Dutch company ReShore is developing breakwater lines for seaweed cultivation to reduce wave energy and protect the seaweed crops.[50] In addition to mitigating against the effects of coastal erosion, this project could help reinforce future offshore cultivation infrastructures.

b. Carbon sequestration

Seaweed is often hailed as the perfect "carbon sink" and multiple projects have sprung up across Europe to attempt to quantify its real carbon sequestration potential. In addition, seaweed aquaculture, through photosynthetic uptake of carbon dioxide, can mitigate local (kilometre-scale) effects of increased ocean acidification by increasing the aragonite saturation state.[51] Given the appeal for carbon credits, a variety of projects are emerging throughout the world to develop methodologies capable of quantifying seaweed's carbon impact. Ocean 2050 is one of the leading projects which aims to link seaweed carbon sequestration to carbon credits.[52] Duarte et al.'s study estimated that the theoretical maximum sequestration from seaweed aquaculture would be 2,48 million tons, larger than global annual emissions (based on a theoretical maximum of 1,500 tons CO_2 $km^{-2}year^{-1}$).[53] Despite the strong interest, the results are still inconclusive and more research is required.[54] A Norwegian initiative called Nordic Blue Carbon is focusing on the knowledge gaps in the long-term carbon storage of macro-vegetation in the North Sea.[55] While most projects tend to focus on "carbon offsetting", new projects are tackling seaweed's contribution to carbon capture differently. Kelp Blue has notably focused on understanding

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[44] Algolesko, "A Propos", accessed 2 December 2022, https://www.algolesko.com/

[45] Colruyt Group, "The first aquaculture products from the project area "North Sea Aquaculture" are a fact AND a success: particularly flavoursome Belgian mussels", (18 September 2018), https://press.colruytgroup.com/the-first-aquaculture-products-from-the-project-area-north-sea-aquaculture-are-a-fact-and-a-success-particularly-flavoursome-belgian-mussels

[46] Aquaponics Iberia, "About", accessed 2 December 2022, https://www.aquaponicsiberia.com/project/ambersea/

[47] North Sea Farm Foundation, "Study on existing market for algal food applications", deliverable D4.1.1 of ValgOrize WP4 Valorize, (September 2019), https://www.noordzeeboerderij.nl/public/documents/Valgorize-D4.1.1A_Study-on-the-existing-market-for-seaweed-food-applications.pdf, 8.

[48] Kelp Forest Foundation, "Kelp Forest Foundation awarded grant by the Safe Seaweed Coalition to assess the biodiversity impact", (23 December 2021), https://kelpforestfoundation.org/kelp-forest-foundation-awarded-a-grant-by-the-safe-seaweed-coalition-to-assess-the-biodiversity-impact/

[49] Hortimare, "High Quality Seedlings", accessed 2 December 2022, https://www.hortimare.com/high-quality-seedlings/

[50] Reshore, "About", accessed 2 December 2022, https://www.reshore.blue/

[51] Seth Theuerkauf, James Morris, Tiffany Waters, Lisa Wickliffe, Heidi Alleway, and Robert Jones, "A global spatial analysis reveals where marine aquaculture can benefits nature and people", PLoS ONE 14:1, (9 October 2019), https://journals.plos.org/plosone/article/file?id=10.1371/journal.pone.0222282&type=printable, 2.

[52] Oceans 2050, "About", accessed 2 December 2022, https://www.oceans2050.com/seaweed

[53] Carlos Duarte, Jiaping Wu, Xi Xiao, Annette Bruhn, and Dorte Krause-Jensen, "Can seaweed farming play a role in climate change mitigation and adaption", Frontiers in Marine Science 4:100 (12 April 2017), https://www.frontiersin.org/articles/10.3389/fmars.2017.00100/full

[54] Steve Hermans, "Oceans 2050 results further seaweed carbon science", Phyconomy, (3 April 2022), https://phyconomy.net/articles/oceans-2050-seaweed-carbon/

[55] Nordic Blue Carbon, "About", accessed 2 December 2022, https://nordicbluecarbon.no/

the life cycle assessment of seaweed, from cultivation to the processing of the raw material.[56] The purpose of this alternative method is to position seaweed as tool for decarbonising value chains (objective of Scope 3 and Scope 4 emissions). This company's plan echoes the scientific community which believes that promoting seaweed-led carbon friendly supply chains and products is more effective in addressing climate change than abstract carbon offsets.

c. Reforestation

With more than 99% of Europe's seaweed projects coming from wild harvesting, the scalability of the seaweed industry will require effective natural resource management to prevent natural stocks from getting depleted. Although strict regulatory frameworks are one way of achieving this objective, other projects in Europe have focused on supporting reforestation projects. Indeed, many seaweed ecosystems (kelp forests in particular) have disappeared from European coastlines as a result of climate change, pollution, overfishing, and excessive touristic activities, leading to lower water transparency. Many university-led conservation projects have emerged throughout Europe:

- The Institute of Marine Research Norway is testing "green gravel" to help improve kelp forest reforestation techniques[57];
- The University of Nice – Sophia Antipolis is studying why seaweed restoration efforts have not functioned despite enhanced water treatment policies[58];
- The University of Barcelona successfully tested active revegetation techniques to promote seaweed forests in sea urchin barren grounds[59];
- The University of Trieste is analysing how to restore natural coastal habitats that have been destroyed and assess the capability of the target species to colonise new areas far from the parental population.[60]

Seaweed reforestation is also attractive for businesses. The Portuguese company Seaforester is working with local communities to replant seaweed in order to restore coastal ecosystems.[61] They achieve this by providing training to local partners to use their seeding stones technique and bring in funding from their partners to accelerate seaweed reforestation efforts.

4.6 Regulatory

Regulations play a critical role in supporting the development of the seaweed industry. At the European level, various regulations are already in effect and lay the foundations for national seaweed policies.[62]

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[56] European Commission, "KELP-EU: "Kelping the EU"

[57] Stein Fredriksen et al, "Green gravel: a novel restoration tool to combat kelp forest decline", *Scientific Reports* 10:3983, (4 March 2020), https://www.nature.com/articles/s41598-020-60553-x

[58] M Susini, L Mangialajo, T Thibaut and A Meinesz, "Development of a transplantation technique of *Cystoseira amentacea* var. *stricta* and *Cystoseira compressa*", *Hydrobiologia* 580 (April 2007), https://link.springer.com/article/10.1007/s10750-006-0449-9

[59] Alba Medrano, Bernat Hereu, Maria Cheminson, Marta Pages-Escola, Graciel la Rovira, Jordi Sola, and Cristina Linares. "From marine deserts to algal beds: *Treptacantha elegans* revegetation to reverse stable degraded ecosystems inside and outside a No-take marine reserve", *Restoration Ecology* 28:3, (May 2020), https://onlinelibrary.wiley.com/doi/10.1111/rec.13123

[60] Annalisa Falace, Elisa Zanelli, and Guido Bressan, "Algal transplantation as a potential tool for artificial reef management and environmental mitigation", *Bulletin of Marine Science Miami* 78:1, (January 2006), https://www.researchgate.net/publication/233528908_Algal_transplantation_as_a_potential_tool_for_artificial_reef_management_and_environmental_mitigation

[61] Seaforester, "About", accessed 2 December 2022, https://www.seaforester.org/

[62] In the EU, the main regulations are the Habitats Directive 92/43/EEC, the Maritime Spatial Planning Directive 2014/89/EU, the Marine Strategy Framework Directive 2008/56/EC, the Water Framework Directive 2000/60/EC, the Alien Species Regulations 1143/2014/EU and 708/2007/EC, and the Environmental Impact Assessment Directive 2011/92/EU. The Organic

Yet at the national level, legislation governing seaweed activities is sparse, very heterogenous, and opaque. Rather than undertaking an analysis per country, this section will identify the main regulatory shortcomings for seaweed activities throughout Europe.

There are many ways through which seaweed harvesting and cultivation can be regulated: licenses or permits, quotas by area, individual quotas by boat, production size and rotation systems. The choice is often culturally rooted in each State's Maritime Spatial Planning (MSP) policies, and it is important to underline regulatory differences between countries concerning the access to foreshore and coastal resources. In France, Spain, Portugal, and Italy, the beach, foreshore, and the sea are public domain and are under the responsibility of the State (and the use of these maritime spaces is at the discretion of the authorities). In these countries, regulations are spearheaded by regional administrations, with the consultation of industry stakeholders, before being approved by the national public authorities. In other countries, the maritime space can belong to the State or to private landowners. As such, in Norway for instance, processing industries harvest raw material directly and the total amount of landings is fixed by the industry based on two conditions: the availability of the stocks and their needs. Cultural differences notwithstanding, the European regulatory landscape for the seaweed industry can be summarised in three broad categories of practices.

a. Slow arrival of seaweed specific strategies and policies

At the supranational level, the "imprint of Europeanisation is particularly visible in the governance of Europe's considerable maritime areas" but questions remain "on how well scales of governance have been translated downward" from EU directives to Member States.[63] All Member States have approved (or are in the process of approving) a policy to implement the EU's 2014 Maritime Spatial Planning (MSP) Directive. Yet seaweed harvesting and cultivation is not always included in these policies. It should be noted that there is no obligation for a Member State to include specific sectors in their plans[64] and the importance of seaweed varies greatly in each Member State's marine policies, with some countries not mentioning seaweed at all while others, such as Denmark, provide detailed strategies on the added-value of the marine resource (cf Table 4.1 below). These disparities are also likely caused by the differing water qualities of the different European maritime spaces. Indeed, the Baltic Sea's low salinity, lack of hard substrata, and extremely eutrophicated areas make seaweed cultivation and harvesting less interesting than in the North Sea or Atlantic Ocean.[65] Finally, most countries do not have any specific regulatory framework for seaweed cultivation – unlike seaweed harvesting which is slightly more regulated – and often rely on general environmental and aquaculture regulations, with the exception of three countries which stand out:[66]

Food Regulation 2018/848/EU has specific rules for the cultivation of organic algae (Part III: Production rules for algae and aquaculture animals, 2. Requirements for algae). When addressing the topic of food safety of macroalgae to be used as food products or ingredients, the Novel Food Regulation 2015/2283/EU applies to all species not previously consumed in Europe, and a specific Recommendation (2018/464/EU) exist to monitor the metal and iodine content in seaweed, and products based on seaweed. For more information, please read Leinemann, Felix and Valentina Mabilia, "European Union Legislation and Policies Relevant for Algae" in *Grand Challenges in Biology and Biotechnology* (January 2020), https://link.springer.com/chapter/10.1007/978-3-030-25233-5_16

[63] Augustus Pendleton and Liam Carr, "Conflicts between traditional and modern governance structures in Irish seaweed harvesting", *Local Environment,* (August 2022), https://www.seaweed.ie/pdf/70542.pdf, 2.

[64] Article 8 of Directive 2014/89/EU on setting-up of maritime spatial plans only list aquaculture as a possible activity to include in the plans, without prejudice to Member States' competences. Nevertheless, the European Commission has published several recommendations on the inclusion of algae in MSP, notably in its recent Communication "Towards a strang and sustainable EU algae sector".

[65] Florian Weinberger, Tiina Paalme and Sofia Wikstrom, "Seaweed resources of the Baltic Sea, Kattegat and German and Danish North Sea coasts", *Botanica Marina* 63:1, (12 November, 2019), https://www.degruyter.com/document/doi/10.1515/bot-2019-0019/html?lang=en

[66] Maria Teresa Camarena-Gomez, Anu Lähteenmäki-Uutela, and Kristian Spilling, "Macroalgae production in Northern Europe: Business and government perspectives on how to regulate a novel blue bioeconomy", *Aquaculture* 560, (15 November 2022), https://www.sciencedirect.com/science/article/pii/S0044848622005506#bb0060

- Iceland is revisiting its entire blue economy strategies and policies, establishing several initiatives towards the implementation of an MSP legislation and blue bioeconomy strategy. More importantly, the country is undergoing a parliamentary process to draft specific seaweed cultivation legislation, in addition to their already specific seaweed harvesting legislation.[67]
- France, despite not having any specific legislation for seaweed harvesting or cultivation, was the first European country to establish a specific evaluation of the use of seaweed for human consumption as non-traditional food substances.[68]
- Denmark created a specific seaweed farming permit as a result of the environmental authorities' interest for anti-eutrophication tools and motivation to improve the overall water quality in the Baltic Sea.[69]

b. Attempts to facilitate administrative processes

The multisectoral nature of the seaweed industry makes it particularly complex to regulate. To begin with, the EU only sets guidelines and recommendations for aquaculture, and Member States are responsible for regulating their respective marine aquaculture activities. Yet the complexity of regulatory procedures is systematically highlighted as one of the key bottlenecks in the scalability of the European seaweed industry. Some countries in Europe have attempted to remedy this issue by reducing the number of regulatory authorities for seaweed activities. This is notably the case in some Baltic countries as well as in Iceland, where one agency is tasked with overseeing the deliverance of seaweed harvesting or cultivation permits. This observation however is biased by the fact that most of these countries do not have a large seaweed industry or, for example, in the case of Poland, that the aquaculture sector is not the main focus for the blue economy.[70] Indeed, in most basins defined in Poland's MSP strategy projects are only considered when they create synergies with wind energy production.[71] Yet most countries in the EU, especially those engaging in seaweed harvesting and cultivation, have complex regulatory regimes. In Denmark for instance, "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" and "this division of responsibility for mariculture crops complicates the process of obtaining licenses for IMTA." [72] In France, the multistakeholder processes implemented in aquaculture permits require all seaweed projects must go through State, regional, and local regulations.[73] In Spain as well, aquaculture is mainly regulated by regional governments (each with different procedures and standards) and by a set of basic general legislation issued by the central government.[74]. Outside the EU, in Iceland, the current aquaculture licensing process is even more complicated: smaller operations are reported to the local Environmental

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[67] Maria Teresa Camarena-Gomez, Anu Lähteenmäki-Uutela, "European and National regulations on seaweed cultivation and harvesting", EU Interreg BSR funded project "Growing algae sustainably in the Baltic Sea" (GRASS), Workpackage 3.2.a, accessed 2 December 2022, https://www.submariner-network.eu/images/grass/FINAL-GRASS_GoA_3.2._SYKE_regulation_report.pdf, 18.

[68] Centre d'Etude et de Valorisation des Algues, "Edible Seaweed and microalgae : regulatory status in France and Europe", (19 March 2020), https://www.ceva-algues.com/wp-content/uploads/2020/03/CEVA-Edible-algae-FR-and-EU-regulatory-update-2019.pdf, 2.

[69] Michèle Barbier, Benedicte Charrier, Rita Araujo, Susan Holdt, Bertrand Jacquemin, and Celine Rebours, "PEGASUS : Phycomorph European guidelines for sustainable aquaculture of seaweeds", COST Action FA1406, (2019), http://www.phycomorph.org/doc/PEGASUS_SUSTAINABLE_SEAWEED_AQUACULTURE_FULL_RECOMMENDATIONS.pdf, 101.

[70] Camarena-Gomez and Lähteenmäki-Uutela, "European and National regulations on seaweed cultivation and harvesting", 6.

[71] Ibid, 6.

[72] Barbier et al., "PEGASUS : Phycomorph European guidelines for sustainable aquaculture of seaweeds", 101.

[73] Ibid, 97.

[74] For more information, refer to Barbier et al., "PEGASUS : Phycomorph European guidelines for sustainable aquaculture of seaweeds", 104.

and Health Inspection and larger operations to the National Planning Agency. Then the Environment Agency is involved and ultimately the Directorate of Fisheries grants the license.[75]

c. Social license to operate (SLO)

Despite EU directives attempting to establish a common framework from which Member States could improve the seaweed industry, European countries have not been successful in harmonising their practices and standards. Each Member State has its own legislation and regulations when it comes to seaweed (rights to harvest, access to licenses, organic status, levels of iodine and heavy metals). Overall, the regulatory attitudes of Member States can be categorised into three groups: States who are not in a rush because there is not much to regulate (mainly Baltic area)[76], States looking to regulate a thriving business opportunity (Netherlands, Ireland, Norway), and States looking to ensure that seaweed fulfills its environmental protection role (Denmark, France). The absence of standardisation is perhaps most visible in Belgium, where the responsibilities for environmental protection are given to regional governments, resulting in different legal and permitting systems within each jurisdiction.[77]

One informal seaweed regulatory practice which seems to proliferate throughout Europe however is the SLO. This concept describes how informal processes carried out by the public, interfere with the management of common resources (here seaweed activities), and their uses in public and private purposes. This bottom-up initiatives are crucial in establishing a legitimacy, trust, and consent between seaweed producers and other stakeholders which they consult on how to optimise their operations.[78] Such relationships have been documented in Brittany (France), in which "small-medium scale farms that are locally owned are more socially acceptable because they are perceived as more accessible and open to discussion of concerns, more likely to provide jobs to local people and, having lower environmental risk."[79] More importantly, the SLO reinforces the relationship between regulators and local communities because "the absence of regulations negatively influences how communities and stakeholders perceive" the seaweed industry.[80] These processes help to clearly define seaweed industry objectives and provide transparent information on the environmental impacts of seaweed harvesting and cultivation. This bottom-up regulatory practice places coastal communities at the core of seaweed policy making procedures.

[75] Camarena-Gomez and Lähteenmäki-Uutela, "European and National regulations on seaweed cultivation and harvesting", 15.

[76] The disinterest of most Baltic States for aquaculture is visible through the absence of specific aquaculture permits. This creates a deadlock for the seaweed industry in these countries.

[77] B Parker, G Benson and D Schlarb-Ridley, "Regulatory Factsheet 12 – Microalgae in Belgium/ Flanders", EnAlgae project output WP2A10.13, (2014), https://www.enalgae.eu/pdf/Public%20Reports/WP2A10.13%20factsheet%2012%20micro%20Belgium.pdf

[78] Julie Rostan, Suzannah-Lynn Billing, John Doran, and Adam Hughes, "Creating a social license to operate? Exploring social perceptions of seaweed farming for biofuels in Scotland, Northern Ireland, and Ireland", *Energy Research and Social Science* 87 (May 2022), https://www.sciencedirect.com/science/article/pii/S221462962100565X

[79] Suzannah-Lynn Billing, Julie Rostan, and Paul Tett, "Handbook on social license to operate for seaweed cultivation", *GenialG H2020 project* and *Scottish Association for Marine Science,* accessed 2 December 2022, https://www.sams.ac.uk/t4-media/sams/pdf/publications/Handbook-on-Social-License-to-Operate-for-Seaweed-Cultivationv4(2).pdf, 2.

[80] Billing et al, "Handbook on social license to operate for seaweed cultivation", 2.

Table 4.1: Overview of European seaweed regulatory practices

COUNTRY	MSP	SEAWEED INCLUDED IN MSP	ROLE OF SEAWEED IN BLUE ECONOMY STRATEGIES	PERMIT REQUIRED FOR SEAWEED HARVESTING	PERMIT REQUIRED FOR SEAWEED CULTIVATION
Belgium	Yes	No	Food and energy	No permit required	Aquaculture permit
Denmark	Yes	Yes	Nutrient control (ecosystem services), feed	No permit required	Seaweed farming permit and environmental impact assessment
Estonia	Yes	Yes	Not mentioned	Fishing permit	Building and water permits
Finland	Yes	No	Energy	No permit required	Water permit
France	Yes	Yes	Biotechnology, food, ecosystem services	Harvesting permit	Aquaculture permit
Germany	Yes	Yes	Raw materials	No permit required	Water, fishing, and IMTA permits
Ireland	Yes	Yes	Biotechnology and food	Harvesting permit	Aquaculture permit
Italy	No*	No	Not mentioned	No permit required	Aquaculture permit
Latvia	Yes	Yes	Chemical and pharmaceuticals	No permit required	Aquaculture permit
Lithuania	Yes	No	Not mentioned	No permit required	Fishing permit
Netherlands	Yes	Yes	Synergies offshore industries	Harvesting permit	Aquaculture permit
Poland	Yes	No	Not mentioned	No permit required	Cultivation (not specific to seaweed), water, and building permits
Portugal	Yes	Yes	Food	No permit required	Aquaculture permit
Spain	No*	No	Not mentioned	Harvesting permit	Aquaculture permit
Sweden	Yes	No	Aquaculture	No permit required	Water permit (>0,3 ha)
Iceland	No	No	Not mentioned	Contract from landowner	Fishing permit
Norway	Yes	Yes	Food, feed, cosmetics, pharmaceuticals	Harvesting permit	Fishing, water, discharge, and seaweed permits, environmental impact assessment (>10 ha)

* National maritime spatial plans are currently being developed by national authorities, no final plan is available at the time of publishing this report.

The information is compiled from Camarena-Gomez and Lähteenmäki-Uutela, "European and National regulations on seaweed cultivation and harvesting", Barbier et al, "PEGASUS : Phycomorph European guidelines for sustainable aquaculture of seaweeds", and governmental websites of each Member State.

4.7 Recommendations

The production of seaweed in Europe has been slowly declining since the 2000s. The reversal of this trend "will depend on the stable access to raw material, the development of the value-added products and the transfer of expertise between regions where production is well developed and those wishing to develop the industry."[81] This chapter has provided an overview of the key economic, social,

[81] Netalgae, "Seaweed industry in Europe", output of Interreg IVB, https://www.seaweed.ie/irish_seaweed_contacts/doc/Filieres_12p_UK.pdf, 4.

environmental, and regulatory practices undertaken by European countries to strengthen the seaweed industry. Building on these experiences and other reports having studied this issue from a different angle, this paper will conclude by identifying concrete actions which can help to scale the European seaweed sector.

a. Economic
   i. Promote the creation of carbon and nitrogen credits to enable seaweed producers to receive an additional income through ecosystem services.
   ii. Encourage the development of new seaweed regions in Europe by creating cooperation and sharing mechanisms (technology, infrastructure, finance).
   iii. Expand the financing of seaweed infrastructures around Europe by building coalitions of investors looking for long-term impact rather than short term returns. Develop holistic metrics (financial, environment, social, governance, and production criteria) to evaluate the impact of these investments and ensure that public funds are being efficiently used.
   iv. Reinforce cooperation between all stakeholders in the value chain (research, producers, investors, regulators) in order to understand mutual needs and construct a common roadmap.
   v. Promote data transparency and analysis tools to better understand the impact of the seaweed industry. The absence of high-quality sectoral data disincentivises risk-averse investors from financing innovative seaweed projects.

b. Social
   i. Create stronger links between all the stakeholders in the seaweed chain. This grassroots approach allows for a tailored governance which valorises local ecosystem knowledge and promotes the role of coastal communities in the management of coastal resources.
   ii. Support the creation of dissemination tools of research and innovation to industry end-users and the general public (such as EU4Algae).
   iii. Create standardised education and training platforms or organisations to enable all European citizens develop the necessary skills for seaweed farming. The key is to avoid the proliferation of different standards by ensuring that all education and training are harmonised across the EU.
   iv. Promote the use of quality schemes and labels (with thorough controls to safeguard integrity and credibility) to address the growing demand for traceable, sustainable, and high-quality products in the entire value chain.
   v. Identify and promote existing good practices in Member States and develop knowledge sharing procedures (events, reports, meetings) to ensure the dissemination of these practices.

c. Environment
   i. Encourage the long-term and measurable decarbonisation of value chains with seaweed products (Scope 4 emissions).
   ii. Provide clear and simple tools to determine the availability and suitability of marine areas for seaweed activities (expected yields in terms of biomass but also specific compounds, nutrient capture potential, expected impact to support

environmental goals established in EU WFD) As an example the General Fisheries Commission for the Mediterranean (GFCM) launched the Allocated Aquaculture Zones (AZA) toolkit that aims to help countries and municipalities to identify the most suitable areas for aquaculture without impeding on other pre-existing blue industries. With increased competition for space in EU waters, applying such methodologies will be essential to guarantee a long-term growth for seaweed.[82]The EU adopted the "Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030." in May 2021 (COM(2021)236 final)

iii. Create transnational structures to share and document the effects of large-scale cultivation on the marine environment (local hydrodynamics, natural benthic vegetation, local biodiversity, nutrient and GHG balance). This will help authorities to grant licenses for long periods and help farmers to secure long-term funding from investors.[83]

d. Regulatory

i. Simplify and clarify licensing and regulation processes (set up a single national seaweed authority, harmonise administration and requirements within the regions of the same country, provide institutional support to seaweed producers to streamline bureaucratic procedures).

ii. Streamline licensing processes throughout Europe and encourage Member States to compare and homogenise regulatory practices and standards

iii. Increase transparency by creating a central regulatory monitoring tool that updates latest legislations in all EU countries relative to the seaweed industry (as envisaged by EU4Algae).

iv. Encourage Member States to develop specific seaweed legislation (or integrate it into existing aquaculture legislation) because the environmental impact of seaweed is different, and often counteracts, the effects of aquaculture.

[82] Food and Agriculture Organization, General Fisheries Commission for the Mediterranean, "Toolkit on allocated zones for aquaculture: benefits, implementation, and management", (2019), https://www.fao.org/gfcm/publications/studies-reviews/azatoolkit/fr/

[83] For more information on the different environmental parameters to investigate for seaweed farming, please refer to Iona Campbell et al, "The environmental Risks Associated with the development of seaweed farming in Europe – prioritising key knowledge gaps", *Frontiers in Marine Science* 6:107, (22 March 2019), https://www.frontiersin.org/articles/10.3389/fmars.2019.00107/full

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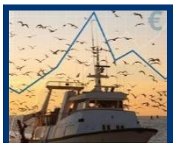

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