Centre for Environment Fisheries & Aquaculture Science

Cefas

Review of species and farming methods

Seaweed in East Anglia (SEA) project

Author(s): Elisa Capuzzo and Isla MacMillan

Date in format: February 2024

This publication is available at www.gov.uk/government/publications

www.cefas.co.uk

Cefas Document Control

Submitted to:	Rikke Nagell-Kleven / Imogen Shipperlee
Date submitted:	February 2024
Project Manager:	Michael Clarke
Report compiled by:	Elisa Capuzzo, Isla MacMillan
Quality control by:	Keith Jeffery
Approved by and date:	26/01/2024
Version:	5
Recommended citation for this report:	Capuzzo, E. and MacMillan, I. (2024). Review of species and farming methods. Seaweed in East Anglia (SEA) project, Cefas project code C8594, funded by Norfolk Investment Framework, pp. 52

Version control history

Version	Author	Date	Comment
1	Capuzzo	June 2023	Outline for discussion with project team
2	Capuzzo, MacMillan	August 2023	
3	Capuzzo, MacMillan	November 2023	
4	Capuzzo, MacMillan	January 2024	K. Jeffery Q'ed
5	Capuzzo, MacMillan	February 2024	G. Malin reviewed / Final

Glossary

Blade, frond or lamina	The leaf-like part of the seaweed thallus
Carposporophyte	A phase of red seaweed life cycle which grows on the female gametophyte
Conchocelis	Life history phase of *Porphyra* spp.
Conchospores	Spores released by conchocelis life phase
Gametophyte	Phase of life history that forms gametangia and releases gametes
Holdfast	Structure for attaching the thallus to the substratum
Isomorphic	Refers to life history phases with a similar form
Sporangium	A cell that releases one or more spores
Sporophyte	Phase of life history that forms sporangia; in *Porphyra* this phase is known as conchocelis, while in the other red seaweeds it is known as the tetrasporophyte
Stipe	Stalk-like portion of the thallus arising from the holdfast
Tetrasporophyte	Life history phase of red seaweeds
Thallus	General term for the whole alga
Zoospores	Mobile spores that move by the means of one or more flagellae
Zygote	A cell formed by the union of two gametes

Executive Summary

- The Seaweed in East Anglia (SEA) project is a collaboration between Cefas, the University of East Anglia and Hethel Innovation Ltd. The project aims to identify steps to develop a sustainable and viable seaweed industry in East Anglia and particularly Norfolk.
- This report scopes the farming methods and species for cultivation off Norfolk, by reviewing current practices and identifying suitable ranges of environmental conditions for growth of brown, red and green seaweed species.
- This document collates and signposts different sources of information (peer-review and grey literature), from the UK, Europe and north-west America.
- The information provided in this review should be considered as “guidelines” for prospective seaweeds farmers and should be critically reviewed against the local conditions of the farm site, farming methods adopted, facilities and vessel available.
- Investigation of the four countries’ registers highlighted that there are 25 approved marine licences for commercial seaweed farming in the UK (12 England, 10 Scotland, 2 Wales and 1 Northern Ireland), however, it is unclear how many of these farms are currently operating, which species are farmed, and the methodologies used (as not all applications provide these details).
- The report considers the following seaweed species: *Saccharina latissima*, *Laminaria digitata*, *Laminaria hyperborea*, *Alaria esculenta*, *Palmaria palmata*, *Porphyra* spp, *Osmundea pinnatifida* and *Ulva* spp. Only some of these species (e.g. *S. latissima*) are currently cultivated successfully in the UK while others (e.g. *Porphyra* spp.) are not farmed as yet due to uncertainty around the species’ life cycle.
- Suitable values of temperature, salinity, underwater light, nutrient concentration, currents, wave height, and depth for farming of the above species were identified where possible. There was a high level of uncertainty around ranges for some of the environmental variables considered, particularly current and wave height, due to lack of observations.
- The review highlighted that there are multiple techniques adopted for farming seaweed (longline, droppers, etc.), and different substrata to grow seaweed (e.g. twine, mesh) which are used in the UK and Europe. Methods should be chosen to suit location, farm size, yield, species farmed, end uses and environmental conditions. Therefore it is not possible to identify “one method that fits all locations”.
- A good body of freely available ‘grey literature’ (e.g. reports, tutorials, videos), in addition to charged courses, was identified, which provides information on how to collect fertile material, nursery set-up and farming at sea, although mainly for brown seaweeds. It is difficult to keep track of these resources and the weblinks may stop working.
- The review was completed by identifying five recommendations to support the development of a seaweed industry in Norfolk and more widely in the UK. These included: the need for more Research & Development on cultivation of additional potential species such as laver; collection and sharing of environmental data at existing seaweed farms in the UK; increased knowledge sharing between farmers around farm structure and farming methods; developing a centralised platform/repository for sharing references and information on cultivation practices; and collection of information on granted seaweed licences and annual seaweed production at the national level.

Contents

1. Introduction

1.1. Seaweed in East Anglia (SEA) project

The SEA project (https://hethelinnovation.com/seaweed-in-east-anglia/) aims to identify steps to develop a sustainable and viable seaweed industry in East Anglia (Figure 1.1). The project, funded by the Norfolk Investment Fund, is delivered by Cefas, University of East Anglia (UEA) and Hethel Innovation Ltd.

The project has three key focus areas:

1) Scoping farming methods and species, as well as co-location opportunities for seaweed aquaculture.
2) Understanding Norfolk's production capability for seaweed-based products with a specific focus on utilisation in agriculture, food and drink products and bioplastics.
3) Developing a roadmap for industry and Algae Cluster development.

Particularly, the regional roadmap will be used by businesses, investors, and local authorities to provide an understanding of the opportunity offered by Norfolk for developing a seaweed economy. While the Algae Cluster will provide the foundation for future demonstrator projects and encourage investment in seaweed-related businesses in the region.

With 90 miles of coastline bordering the North Sea, Norfolk has an opportunity to establish a seaweed industry and seaweed-based value chains in the region. The SEA project addresses current barriers to the development of a seaweed industry in Norfolk and provides the foundation for future projects that could showcase Norfolk's potential as a market leader in the industry, making Norfolk a competitive location to base a seaweed business.

This report is part of the delivery of the focus area 1, listed above. Particularly, it **reviews current seaweed species and farming methods adopted in the UK and more broadly in Europe, as well as the suitable ranges of environmental conditions for optimal growth of key brown, red and green seaweed species**. It collates and signposts (where relevant) different information sources including peer-reviewed papers, project reports, existing marine licence applications, interviews with stakeholders, and project websites.

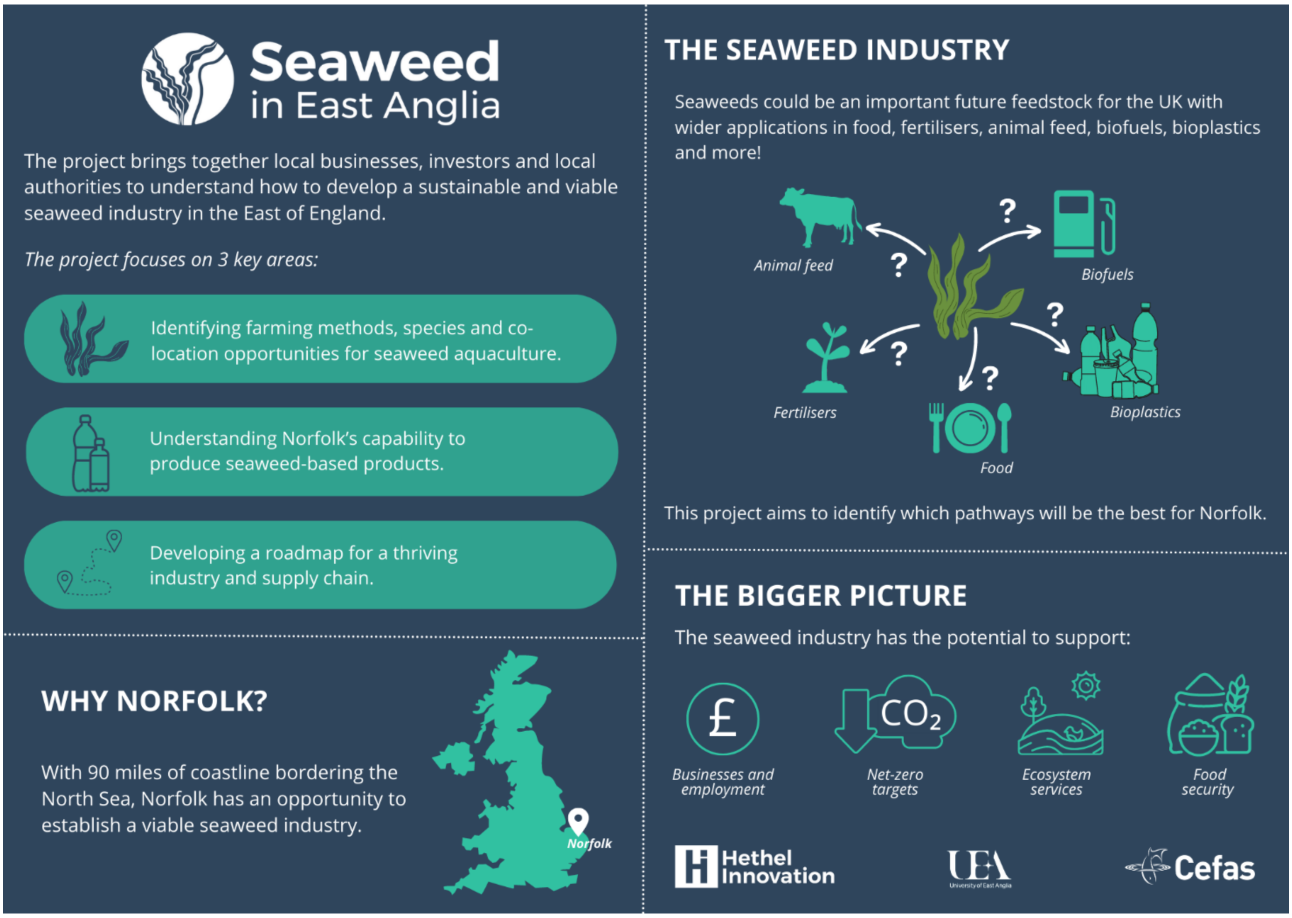


Figure 1.1 Summary infographic for the Seaweed in East Anglia (SEA) project.

1.2. Seaweed industry in the UK

Seaweeds have been harvested from the wild for centuries and traditionally used for food, feed and fertilizers. There is evidence that seaweed has been consumed by humans since the Neolithic in Scotland and Europe (Buckley *et al*., 2023). In the last decade, a resurgence in interest in seaweed has led to the development of seaweed aquaculture, with the first commercial seaweed farm established in 2015 on Rathlin Island, Northern Ireland (Capuzzo, 2022). There is an interest in expanding seaweed aquaculture in England; in fact, the English Aquaculture Strategy (Seafood 2040) suggests that 13,000 tonnes per annum (wet weight) of seaweed could be produced in English waters by 2040 by aquaculture (Huntington and Cappell, 2020).

Seaweed farming in the UK is in its infancy and there are no estimates of current production; however, as of September 2023 there are 25 marine licences for commercial seaweed farming granted in the UK to date (Table 1.1), with more currently progressing through the licencing process. Examples of established seaweed farms in England include the Cornish Seaweed Company, Biome Algae, SeaGrown, Jurassic Sea Farms and recently Norfolk Seaweeds.

Table 1.1 Granted marine licences for commercial seaweed farming in the UK (as per September 2023). Farm areas and dimensions have been converted to hectares for ease of comparison (when provided in the licence application).

Seaweed Company Name	Country	Location	Farm Size (hectares)
Algapelago Marine Limited	England	Bideford Bay, North Devon	100
Aqua Botanika LTD	England	Thatcher's Rock, Torbay, Devon	10
Biome Algae	England	St Austell Bay, Cornwall	
Green Ocean Farming	England	Portland Harbour, Dorset	6
Green Ocean Farming	England	Torbay, Devon	3
Jurassic Sea Farms	England	Portland Harbour, Dorset	
Norfolk Seaweed LTD	England	Blakeney Harbour, Norfolk	5
Penmayn Limited	England	North Cornwall	100
SeaGrown	England	Scarborough, Yorkshire	25
The Cornish Seaweed Company	England	Porthallow Cove, Cornwall	2
Turning Tides LTD	England	Folkestone Harbour	225
West Country Mussels of Fowey	England	St Austell Bay, Cornwall	104
Islander Kelp	Northern Ireland	Rathlin Island	
Aird Fada	Scotland	Lock Scridain, Isle of Mull	50
Argyll Aquaculture	Scotland	East Balvicar Bay, Seil Island	6
GreenSea Solutions Ltd	Scotland	Loch Sunart	1.54
Sea02 Ltd/ Hebridean Wildfoods Ltd	Scotland	Lock Erisort, Isle of Lewis	0.023
Kaly Group Ltd	Scotland	West Side Loch Bay, Loch Dunvegan, Isle of Skye	16
KelpCrofting	Scotland	Pabay & Scalpay, Isle of Skye	13
Lochnell Seaweed	Scotland	Argyll and Bute	0.095
Seaweed Farming Scotland Ltd.	Scotland	Fife and Argyll	0.08
Shore / New Wave Foods	Scotland	Southern end of Kerrera Sound	30
West Coast Seaweed Ltd	Scotland	Badachro, Gairloch, Wester Ross	
Câr-y-Môr	Wales	St David's, Pembrokeshire	3.5
Seaweedology LTD	Wales	Pembrokeshire	4

Seaweed species farmed in the UK include brown seaweed (*Saccharina latissima*, *Laminaria digitata*, *Laminaria hyperborea*, *Alaria esculenta*), red seaweed (*Palmaria palmata*) and green seaweed (*Ulva* spp.). Farming of other red seaweed species such as *Porphyra* spp. (laver) and *Osmundea pinnatifida* (flat fern-weed) is still at the experimental stage (Capuzzo, 2022).

Seaweed biomass can be used as food, feed, fertilizers, and to produce bio-stimulants, nutraceuticals, cosmetics, biofuel, bioplastic and biomaterial. In the UK, around a third of seaweed-related businesses target food and drink production, 19% of the businesses target beauty industry and 13% production of supplements/nutraceuticals (Capuzzo, 2022). The number of UK seaweed-related businesses has more than doubled in the last 5 years (Capuzzo, 2022), following a similar trend as observed in Europe, where seaweed producers increased by 150% in the last decade (Araujo *et al.*, 2021).

Guidelines on applications for a marine licence for seaweed aquaculture in England, developed by Defra, Cefas, MMO and Natural England, will soon be published on the Seafish website. The guidelines summarise the information that needs to be provided by the applicant and captures the key stages of the application process, listing the relevant authorities and other users of the marine area (e.g. commercial fishers, local ferry operators, recreational users, yachting groups, kayakers, rowing clubs and local communities), that should be engaged during the process. Information on the steps and authorities involved in the marine licencing process for seaweed aquaculture can also be found in the Aquaculture Regulatory Toolbox for England (https://www.seafish.org/trade-and-regulation/regulation-in-aquaculture/aquaculture-regulatory-toolbox-for-england/).

1.3. Environmental conditions and site selection

One of the key steps in starting seaweed aquaculture in open water conditions is the site selection for the farm. The decision on site selection can involve scientific, technological, biological, socioeconomic, and legislative considerations; particularly, the correct biological parameters that should lead to good growth performance of the seaweed crop and consequent profit (see review by Buck and Grote, 2018).

Each seaweed species has specific growth conditions, in terms of temperature, salinity, light and nutrient availability, and water motion. When these conditions are known, it is possible to identify areas which would be optimal, suboptimal or unsuitable, for growing that specific seaweed species.

Suitable sites can be identified adopting **spatial modelling and GIS-based approaches**. GIS-based suitability modelling comprises the spatial overlay (intersection) of geo-data layers to find suitable sites for aquaculture, by identifying favourable environmental factors or constraints/limitations (Stelzenmüller *et al.*, 2017). In other words, a 'suitable' site is an area where the production of seaweeds is maximised and the conflicts (with other potential uses) are minimised (Rosijadi *et al.*, 2011). Two sets of variables are usually needed for this type of analysis: selection factors (environmental variables), and selection constraints such as competing uses for space (Rosijadi *et al.*, 2011). Environmental selection factors important for seaweed farming are sea surface temperature, salinity, light availability, dissolved inorganic nutrient concentrations (e.g. nitrogen), current speed and wave height (Capuzzo *et al.*, 2018). Water quality is also an important factor to consider when choosing locations for seaweed farming to avoid risk of contamination by heavy metals and microbiological quality (e.g. *E. coli*; Barbier *et al.*, 2019).

Examples of application of this GIS approach to identify suitable areas for seaweed aquaculture in English waters are available through https://explore-marine-plans.marineservices.org.uk/ (details in report MMO, 2019), or at https://www.dorsetaquaculture.co.uk/opportunities/new/map/ for the Dorset and Devon coastlines. The same GIS approach will also be applied to the area off Norfolk as part of this project under focus area 1.

As part of this GIS approach, relevant environment data layers (e.g. temperature, salinity) are classified to define regions of optimal, sub-optimal and unsuitable conditions for growth of specific seaweed species. The ranking of the different environmental variables is then overlapped to create a composite layer showing the highest suitability. The environmental 'suitability' layer can then be overlaid with spatial-use data (e.g. shipping, fishing areas, offshore infrastructures, Marine Protected Areas) and technical constraints (i.e. specific depth range or exposure for the infrastructure of the farm) to refine the site location, minimizing conflicts with other activities.

<u>Water temperature</u> is a key environmental variable as it affects the metabolic rate of seaweeds so has a direct effect on their growth (Kerrison *et al.*, 2015). Kelps, such as *S. latissima*, *L. digitata* and *A. esculenta*, are generally tolerant of low temperatures in winter (i.e. just below 0 °C; see review by Kerrison *et al.*, 2015), although with reduced growth rates. Contrarily, many seaweeds are more sensitive to high temperatures, particularly during summer, and their geographical range is dictated by specific isotherms (e.g. 16 °C for *A. esculenta*; Munda and Lüning, 1977; Sundene, 1962).

Other environmental variables that should be taken into considerations in relation to seaweed farming are:

<u>Salinity</u>: seaweed species can be more (euryhaline) or less (stenohaline) tolerant to changes in salinity; fluctuations in salinity can have severe effects on less tolerant seaweeds, potentially leading to the death of the algae. For example, dulse (*P. palmata*) is less tolerant to salinities below 30 compared to sugar kelp.

<u>Light availability</u>: without light seaweeds would not be able to carry out photosynthesis and therefore survive. Light penetration through the water column can be reduced by suspended sediments (e.g. resuspended from the sea floor), therefore it is important to select a site with clear water and low sedimentation. Shallow areas, with high levels of sediments, should

then be avoided. However, too much light also has detrimental effects as it can lead to cellular damage and death (photoinhibition; see review by Hanelt and Figueroa, 2012).

Nutrient concentration: seaweed require nutrients (e.g. nitrogen and phosphorus) for growth and metabolic processes. The uptake rate of the dissolved nutrients from the surrounding water is affected by factors such as light availability, temperature, desiccation, water movement, and the chemical form of nutrients (Harrison and Hurd, 2001).

Finally, water movement around the seaweed is also important and has multiple implications for the algae (from Birkett *et al.*, 1998; Lobban and Harrison 1997). It affects: i) the shape and positioning of the kelp in the water; ii) how the nutrients are used in the algae - in sheltered sites the main part of the growth is allocated to the frond, while in more exposed sites, anchoring structure (holdfast) and stipe received higher energy for growth (Sjøtun and Fredriksen 1995); iii) high water movement can promote breakage of the frond or dislodgement of the algae; iv) continuous movement of the frond with current maximises the light harvesting capacity of the algae; v) it replenishes nutrients around the thallus; vi) it defends the seaweed against grazers.

Studies on recommended wave height or current speed for seaweed farming are very limited, as the tolerance of the farm to offshore conditions depends on the farming method, farm configuration and engineering structure. Recommended conditions of wave height and current speed would need to consider not only the engineering and anchoring standards of the farms but also the ability of seaweed (from small sporophytes to full grown adult plant) to remain attached and grow on the chosen substratum. Therefore, data collected at existing seaweed farms is key. For example, Mooney-McAuley *et al.* (2016) suggested consideration of nearshore areas with < 2 m swell and currents < 1.5 m s^{-1} / 3 knots, whilst Kerrison *et al.* (2015) recommend a minimum water flow of 0.1 m s^{-1}.

Bak *et al.* (2018) reported successful kelp farming with current speeds of 0.1-0.25 m s^{-1} and occasional significant wave heights between 3-6 m at a farm in the Faroe Islands. In fact, the same farm withstood a maximum significant wave height of 7-8 m (Buck and Grote, 2018). Another study of *S. latissima* farmed at an offshore location in the German Bight showed that kelp withstood a maximum current velocity of 1.52 m s^{-1} and wave height of 6.5 m.

The possibility of a catastrophic loss of the farm during storm events must also be factored into the site placement, so a detailed study of the local wave climate should be considered (Capuzzo *et al.*, 2014). In this context, the WaveNet network (https://www.cefas.co.uk/cefas-data-hub/wavenet/) provides continuous data for wave height along the English coast.

Depth requirement for the farm is dependent on the technique adopted for cultivation of seaweeds (e.g. ropes, textiles), the structure of the farm, accessibility via boat etc. As an example, pilot farms in Scotland and Northern Ireland are installed in water depths between 2 to 25 m (van der Molen *et al*., 2018). However, the location of Ocean Rainforest farm, Faroe Islands, is at a location between 50 and 70 m deep (Buck and Grote, 2018). In this study optimal depth was considered > 4 m with no upper limit.

The following sections of the report (2 to 4) summarise the optimal, suboptimal, and unsuitable environmental ranges for the most commonly farmed seaweeds in the UK. These have been divided in the three groups of brown, red and green algae. It is important to remember that the environmental thresholds presented have been obtained from literature based on laboratory experiments and/or observations in situ at other farm locations. Therefore the thresholds must be considered as guidelines.

2. Brown seaweeds

Brown seaweeds belong to the class Phaeophyceae and include the largest of all the seaweeds (Bunker *et al.,* 2017). They are commonly visible when visiting UK coasts, for example washed up at the top of the beach, covering rocks or forming underwater kelp beds. The brown or olive-green colour comes from pigments present in the brown seaweed, particularly chlorophyll c and fucoxanthin. They thrive in different marine habitats including bedrock, boulders, cobbles, pebbles and sand scoured habitats (Bunker *et al.,* 2017).

There are around 185 species of brown seaweeds along the UK coast, ranging from microscopic species to giant species such as *Laminaria hyperborea* (more than 2 m long), that form large underwater forests (Bunker *et al.,* 2017). However, only a handful of these species is currently farmed in the UK and Europe.

Brown seaweeds belonging to the kelp group consist of three parts: a flat blade or lamina, a flexible stipe that supports the blade and a holdfast, a claw-like structure which anchors the kelp to the substratum. *Laminaria hyperborea* is the dominant kelp in Britain and forms dense forests.

Kelps have traditionally been harvested from the wild in different parts of the UK, for use as food, feed and fertiliser, as well as for the production of soda ash (for soap and glass making), and extraction of iodine and alginates. They have been commercially farmed in the UK since 2015.

2.1. Farming process and methods

To successfully farm seaweed, it is important to understand the life history of species of interest. Brown seaweeds have two phases in their life history: a gametophyte and a sporophyte. These two phases can look completely different; for example, for kelp the sporophyte is the large seaweed visible in coastal areas while the gametophyte is a microscopic and invisible to the naked eye.

Broadly, farming of kelp species involves the following steps (Figure 2.1):

i. Collection of adult fertile individuals from the wild;
ii. Hatchery stage – release of gametophytes and production of sporophytes; attachment of sporophytes to twine spools or directly seeded to a suitable substratum with glue / bio-binder;
iii. Out-planting of seeded twine/substratum at sea between October-February; for example, brown seaweed is farmed at sea on longline systems with moorings every 100 m, 1.5 m below the surface;
iv. Harvesting of farmed seaweed (usually between April and June);
v. Post-harvesting process / primary processing (e.g. drying, ensiling) to stabilise seaweed biomass.

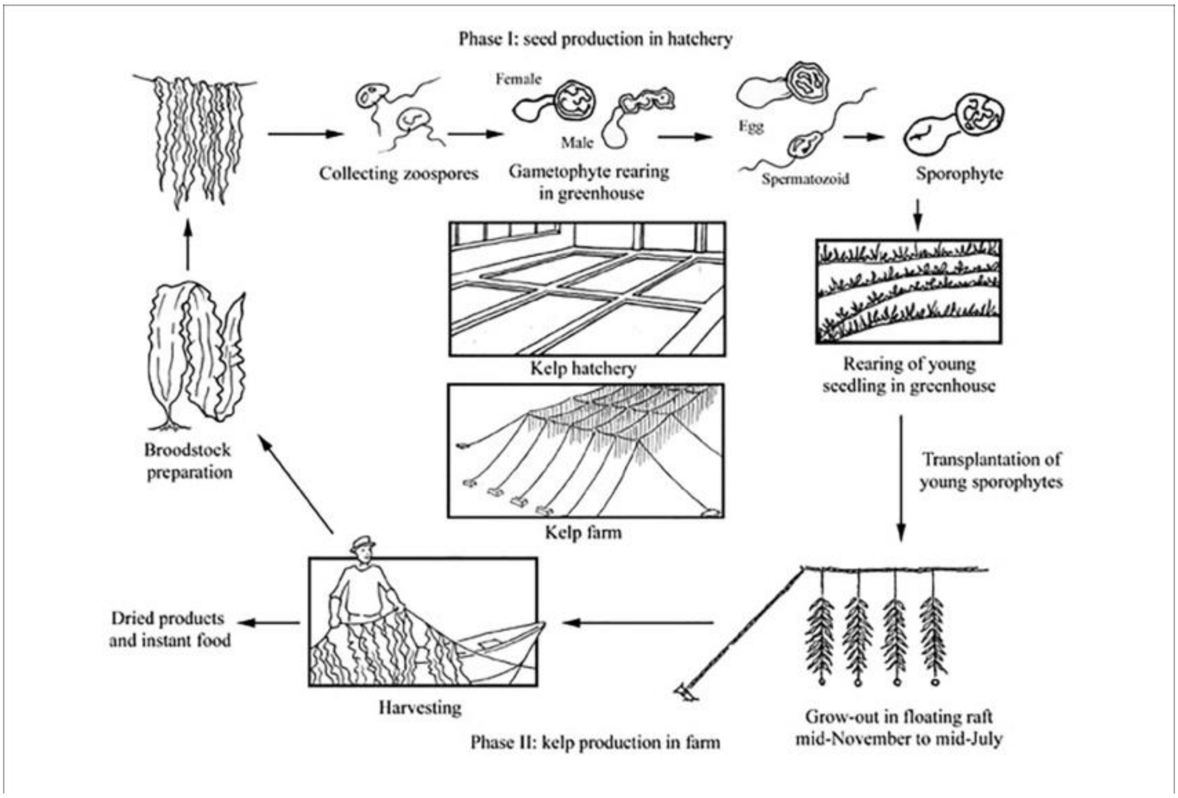


Figure 2.1 Production cycle of the kelp *Saccharina japonica* in China (from FAO, 2004).

Multiple reports and operating procedures are available online freely, describing in detail the process and key phases of seaweed farming, particularly for brown seaweed. A list of some of these reports and associated weblinks is provided below and we refer the reader to these documents for specific information on equipment needed, photos and videos of the different stages of farming. One-day or one-week courses on seaweed farming can also be purchased from the Seaweed Academy (https://seaweedacademy.co.uk/) in Scotland.

Examples of freely available resources (reports, tutorial) on seaweed farming

UK and EU

- Genialg Project e-learning training courses: https://genialgproject.eu/e-learning-course/
- EnAlgae Project Best practice guidelines for seaweed cultivation and analysis (Mooney-McAuley *et al.*, 2016) https://www.enalgae.eu/pdf/Public%20Reports/WP1A5%20Macroalgae%20BP.pdf
- Cultivation of *Laminaria digitata* by Bord Iascaigh Mhara (BIM) Irish Sea Fisheries Board (Edwards and Watson, 2011) https://bim.ie/wp-content/uploads/2021/02/BIM,Aquaculture,Explained,Issue,26,-,Cultivating,Laminaria,digitata.pdf
- Seaweed cultivation manual by NAFC Marine Centre, University of the Highlands and Islands:

https://www.researchgate.net/publication/349686158_SEAWEED_CULTIVATION_MANUAL_Shetland_Seaweed_Growers_Project_2014-16

- Aberdeenshire Council Seaweed Cultivation (Northern Light Consulting, 2021) http://publications.aberdeenshire.gov.uk/dataset/0964f372-1a23-447a-bf2c-828da1ed78a1/resource/fe54ef76-d2f4-467c-912f-c2ad9e82e74e/download/aberdeenshire-council---cids-seaweed-cultivation-feasibility-study-july-2021-13092021.pdf

North America

- Kelp farming manual New England https://maineaqua.org/wp-content/uploads/2020/06/OceanApproved_KelpManualLowRez.pdf
- Greenwave, seaweed farmer in Long Island Sound https://www.greenwave.org/hub
- New England Seaweed culture handbook (by the University of Connecticut and University of New Hampshire) and youtube videos https://repository.library.noaa.gov/view/noaa/36147/noaa_36147_DS1.pdf https://www.youtube.com/playlist?list=PLjT8rkCZmfJex1Eyr0IIlXlW8lsp90WPC

The part/s of the seaweed containing the fertile material is cut off and taken to the hatchery. The adult seaweeds should be collected in proximity of the farming site, however, whilst existing regulation does not provide a specific collection radius from the farm this is sometimes decided on a case-by-case basis. Campbell *et al.* (2019) suggested gathering fertile seaweed from sites preferably within 2 km from the farm sites, up to a maximum of 20 km, within the same water body.

The fertile seaweed tissues could be sent to an external hatchery, which would use the tissue to prepare and biobank gametophytes, and prepare and send seeder strings back to the farmer on request (e.g. SAMS in Scotland, Hortimare in the Netherlands). The external hatchery should prove its ability to avoid contamination of culture strings with seaweed strains from other locations, therefore minimizing biosecurity risk.

For a detailed discussion on the best material to use for the string or twines to be seeded with sporophytes and gametophytes we refer the reader to the study by Kerrison *et al.* (2019). As an alternative to strings or twines, macroalgae can also be cultivated on textiles; however, due to the larger surface area, textiles require either direct in-situ seeding at the farm or a very short hatchery period (Kerrison *et al.*, 2018). Furthermore, gametophytes and sporophytes can be made adhere to the material using a binder solution. Kerrison *et al.* (2018) demonstrated that there was no significant difference in growth of *S. latissima* when cultivated on twines or textiles, particularly seeding of sporophytes on textile with binder was shown to be successful cultivation method.

Deployment should be carried out in late autumn/winter (see farming calendar in Figure 2.2), in line with the biology of the seaweed species cultivated. In fact, juvenile kelp in the wild establish around this time of the year, when light and temperature are low, there is a reduced competition for nutrients with phytoplankton and a low risk of epiphytes (Mooney-McAuley *et al.*, 2016).

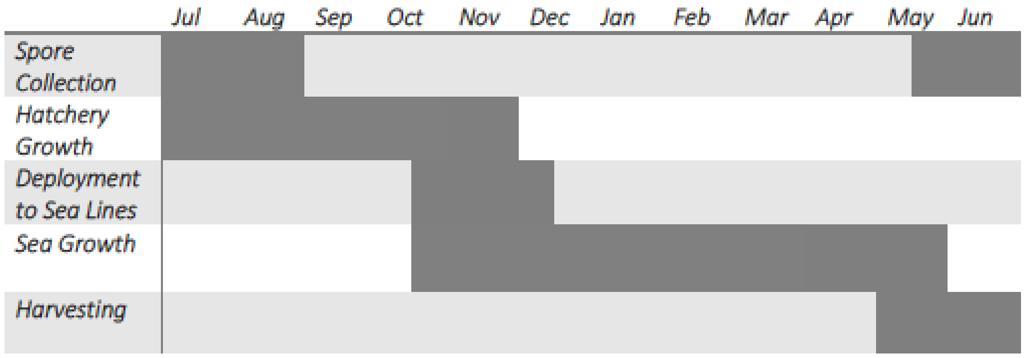


Figure 2.2 Farming calendar for *Laminaria digitata* (from Rolin *et al.*, 2016).

The deployment technique adopted will depend on the type of farm structure, on the cultivation material (e.g. twine or textile), the size of the boat and facilities available. The structures and layout of seaweed farms can be variable, depending on multiple factors including size of the farm, environmental conditions at the site (e.g. depth, exposure), species cultivated and expected yields.

In general, a seaweed farm will have two main components: moorings and longlines supported by floating buoys. According to the report by Northern Light Consulting (2021) there are 3 main options for farm design: i) individual longlines, ii) grid-based systems and iii) double header longlines (Figure 2.3). Individual longlines consist of 100 to 200 m long seeded lines suspended in parallel lines approximately 1.5 m below the surface (Figure 2.3a). In grid-based system a rope is positioned around 2-3 m below the surface, anchored in all direction and supported by surface buoyancy aids; seeded ropes are then positioned in the grid system at set distance apart (Figure 2.3b). For example, KelpCrofters, farming in the waters south of Pabay (Scotland), adopt a grid with heavy ‘gable’ ropes supporting around 6-8 km of growing lines (https://kelpcrofters.com/news/new-seaweed-farm-installed). The double header longlines are commonly used when the seaweed farm repurposes equipment for a mussel farm (Figure 2.3c and d); for example, this method is used by Car-y-Mor in Wales (https://www.carymor.wales/about-us). We refer the reader to the Northern Light Consulting (2021) report for estimates of the initial equipment and capital (start-up costs and operating costs) needed for the methods above.

Other seaweed farms in the UK and in the wider European area adopt and/or are testing different farming methods and structures. For example, the Cornish Seaweed Company in Porthallow Bay (South-West England) farms seaweed on 6 m droppers, hanging from a near surface header line (Figure 2.4; Corrigan *et al.,* 2023). Ocean Rainforest in the Faroe Islands constructed the Macroalgae Cultivation Rig (MACR; Figure 2.5), suitable for cultivation at wave-exposed sites with water depth of 50-200 m. In this configuration, seeded lines are attached to a fixed line (at around 6-10 m depth) and kept in a vertical position by a buoy (Bak *et al.,* 2018). Droppers are suitable in clear waters but would not be recommended in more turbid waters as the seaweed growing at the deeper end of line might not receive enough light.

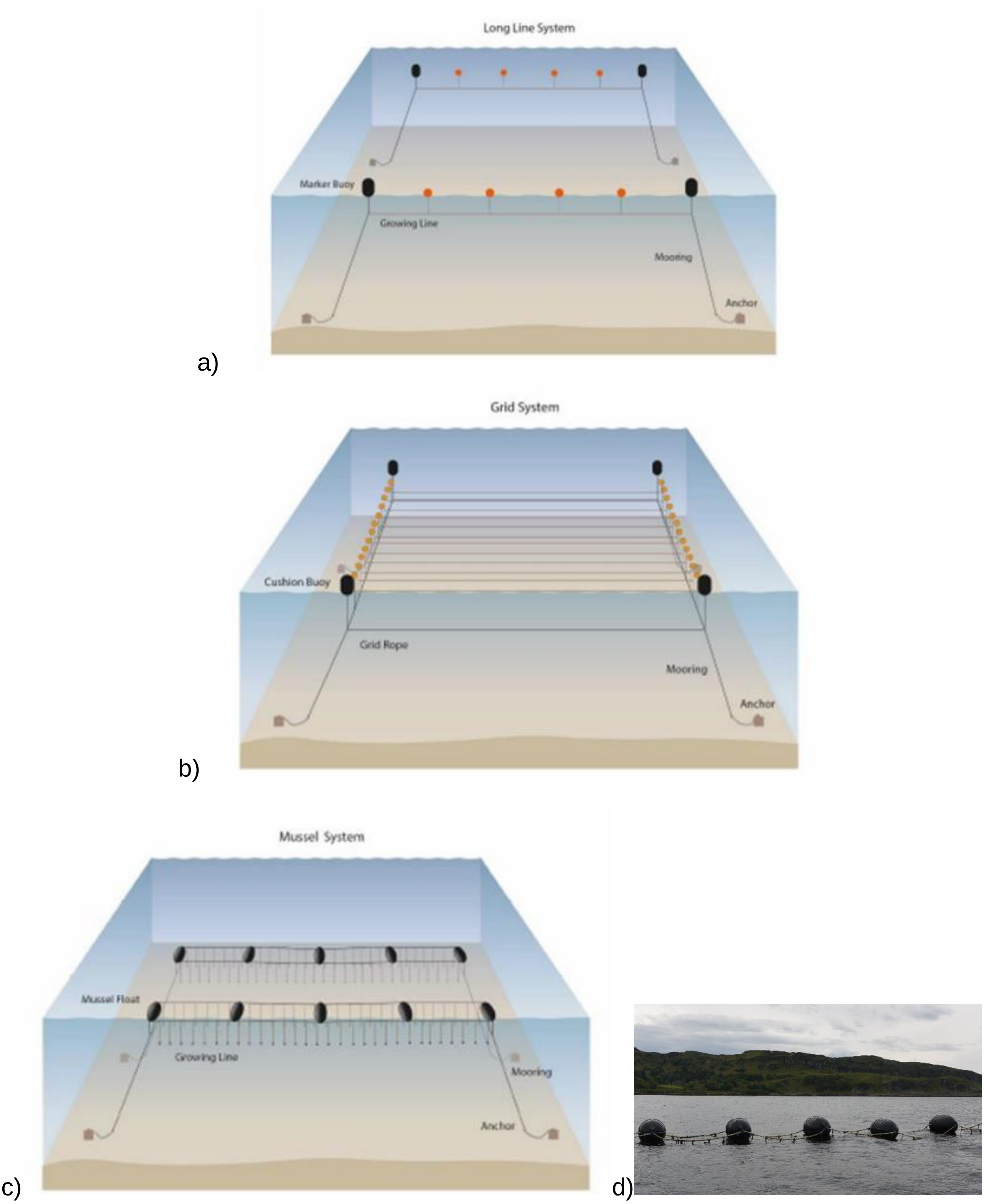


Figure 2.3 Diagrammatic views of seaweed farm design options a) individual longlines; b) grid-based system; c) double header longlines; d) SAMS experimental seaweed farm off Oban (source SAMS Enterprise 2019, in Northern Light Consulting 2021; photo credit: Elisa Capuzzo).

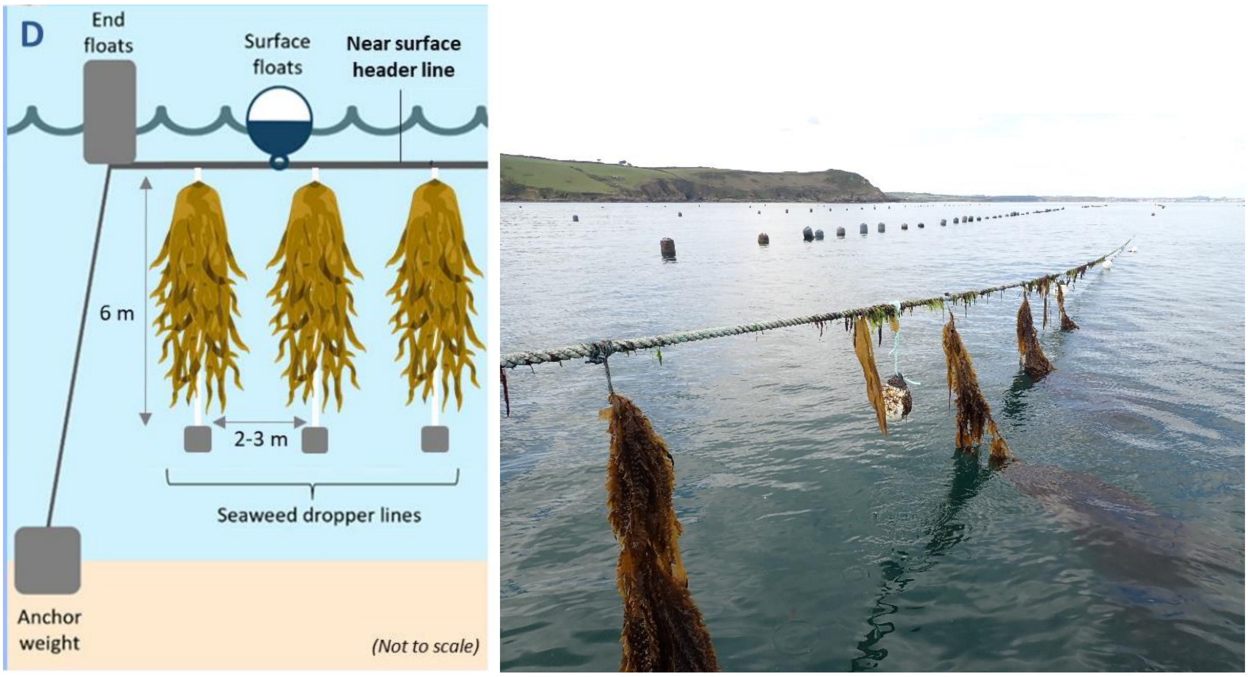


Figure 2.4 Longline system suspending seaweed droppers adopted at the Cornish Seaweed Company farm in Porthallow Bay for farming *Saccharina latissima* (from Corrigan *et al.,* 2023; photo credit: Cat Wilding).

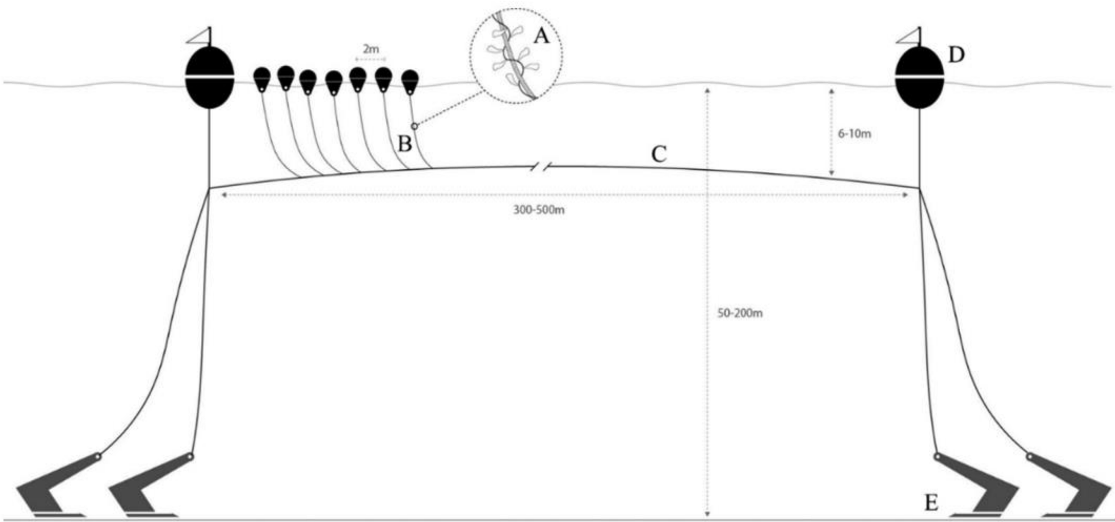
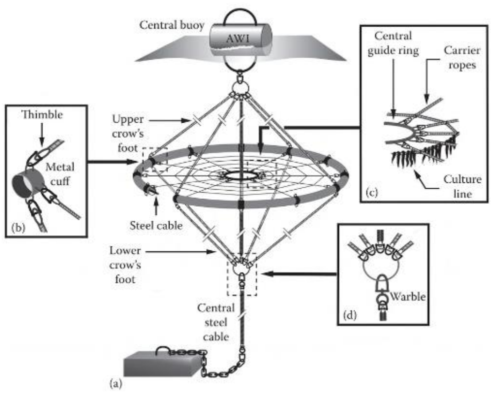


Figure 2.5 Schematic diagram of a Macroalgal Cultivation Rig (MACR) constructed by Ocean Rainforest in the Faroe Islands for farming of *Saccharina latissima*, *Laminaria hyperborea* and *Alaria esculenta* (Bak *et al.,* 2018).

A ring structure within wind turbines parks was tested in the North Sea in the 2000s (Figure 2.6a). *S. latissima* plants at this offshore farm in the German Bight withstood a maximum current velocity of 1.52 m/s and wave height of 6.46m (Buck and Buchholz, 2005). It is likely that farming at higher currents and wave height would be possible, however, to our knowledge, there is very limited evidence in literature. For example, the Ocean Rainforest farm, in the Faroe Islands, withstood a maximum significant wave height of 7-8 m (Buck and Grote, 2018).

An alternative to culture seaweed in lines or grids is to adopt 2D substrates such as fabric sheet or fine mesh. These have been developed by AtSeaNova under the European R&D project AT-SEA, using 2x10 m fabric modules (Figure 2.6b). This system requires automated machinery for harvesting the sheets which are seeded using a bio-binder spray to ‘glue’ the sporophytes to the material (Tullberg *et al.,* 2022). A more recent design of linear net systems is currently being tested in the North Sea off the coast of the Netherlands under the ZeewierSEEDER project at the North Sea Farmers site (Figure 2.6c).

a) 

b) 

c) 

Figure 2.6 a) Offshore ring device for the cultivation of seaweed, adopted to farm *Saccharina latissima* in the German Bight (from Buck and Grote, 2018); b) *Saccharina latissima* cultivated on textiles (https://www.innovationintextiles.com/sioen-founds-spinoff-company-to-sell-its-textile-based-seaweed-cultivation-substrates/) c) linear net system currently being tested at the North Sea Farmers site off the Netherlands (https://www.northseafarmers.org/news/20231221-zeewierseeder).

It is important to monitor the growth of the farmed seaweeds to determine whether there is any damage, or entanglement, to the structure and lines or nets and to estimate the seaweed biomass (Mooney-McAuley *et al.*, 2016).

Site monitoring should be carried out once a month (or more frequently if resources allow) and after storm events, which may cause loss of buoys, breakage of culture strings or entanglement of lines. Environmental conditions that should be monitored include sea temperature, underwater light, nutrient concentration and turbidity; these environmental conditions affect seaweed growth but also provide information on the influence of seaweed farming on the surrounding environment (Mooney-McAuley *et al.*, 2016).

Harvest of seaweed is usually carried out at the start of summer, although this may vary between years and locations. In general, the harvest should occur when seaweed biomass is at the highest but before biofouling starts affecting the seaweeds and/or the seaweed start degrading in seawater. Regular monitoring of the farm will help determine the most appropriate time for harvesting (Mooney-McAuley *et al.*, 2016).

2.2. *Saccharina latissima*

Saccharina latissima, or sugar kelp, can grow to 1.5 m in length; it is characterized by a crinkly, dimpled, ruffled appearance and has a light to dark brown colour (Figure 2.7; Bunker *et al.*, 2017). The frond is undivided, without a midrib, and it has a short stipe; it grows quickly from late winter to spring (White and Marshall, 2007).

In the environment it is present on rocky substrata in disturbed habitats (e.g. sand scoured) as well as in sheltered sea lochs (Bunker *et al.*, 2017). It is often found on unstable rocks and boulders, with adaptations like its flexible stipe reducing leverage and thus movement on the boulder (https://www.marlin.ac.uk/species/detail/1375). Sugar kelp prefer low to moderate water movements (between 0.1m/s to 1m/s) but can grow well also in strong currents up to 1.5m/s (Kerrison *et al.*, 2015).

S. latissima is the seaweed species most commonly farmed in the UK and its biomass is suitable for multiple uses from food to biofuel production (Capuzzo, 2022). Environmental ranges of suitable/unsuitable conditions for farming sugar kelp are given in Table 2.1.

Figure 2.7. *Saccharina latissima* (sugar kelp) farmed in Scotland (photo credit: Elisa Capuzzo).

Table 2.1 Environmental thresholds for growth of *Saccharina latissima*. SST = sea surface temperature; K_d = light attenuation coefficient; PAR = photosynthetic active radiation; TOxN = total oxidised nitrogen (nitrate+nitrite).

Environmental Factor	Optimal	Suboptimal	Unsuitable	Reference
Minimum SST (°C)	>5	2-5	<2	Bolton and Lüning, 1982; Kerrison *et al.*, 2015
Maximum SST (°C)	<16	16-18	>18	Bolton and Lüning, 1982; Kerrison *et al.*, 2015
Minimum Salinity	>24	15-24	<15	Kerrison *et al.*, 2015
K_d(PAR) 10% light depth (m)	>2	1-2	<1	van der Molen *et al.*, 2018
Winter TOxN (mmol/m^3)	>10	4-10	<4	Broch and Slagstad, 2012; Kerrison *et al.*, 2015
Current (m s^{-1})	0.1-1.5*		<0.1 & > 1.5	Kerrison *et al.*, 2015; Mooney-McAuley *et al.*, 2016; Buck and Buchholz, 2005
Maximum wave height (m)	<6**		>6	Buck and Buchholz, 2005; Buck and Grote, 2018
Water depth (m)	>4***		<4	Mooney-McAuley *et al.*, 2016

* Low-moderate flow but can also grow in strong current (Kerrison *et al.*, 2015; Zhu *et al.*, 2021).

** There is some limited evidence that seaweed farms can withstand higher wave heights e.g. Ocean Rainforest in the Faroe Islands withstood a maximum significant wave height of 7-8 m (Buck and Grote, 2018).

*** Maximum depth will depend on the type and structure of the farm; for example, the Ocean Rainforest farm site has a water depth of 50-70 m; their cultivation rig can be deployed up to depths of 200 m (Bak *et al.*, 2018).

2.3. *Laminaria hyperborea* and *Laminaria digitata*

Laminaria hyperborea or Forest Kelp is the dominant kelp around the UK coast, forming dense stands of large upright individuals in clear sub-tidal waters with rocky substrata. It can grow exceptionally to 3.6 m high and has a segmented lamina expanding from a long, rough, cylindrical stipe and attached via a claw-like holdfast (Bunker *et al.*, 2017). Individuals are tough and the stipe may snap when bent double. It can have other epiphytic algae and animals growing on the stipe and holdfast. (Bunker *et al.*, 2017). High water motion increases productivity and growth in *L. hyperborea* by improving uptake of nutrients (Smale *et al.*, 2020).

Laminaria digitata or oarweed is also a common kelp in UK waters. It can live for up to 10 years or so and the thallus is up to 1.5 m in length (Bunker *et al.*, 2017). The blade or lamina is leathery and a shiny brown colour, with a digitate sheet-like oval blade, and the stipe is also oval, usually clear of epiphytes and very flexible Bunker *et al.*, 2017). It grows rapidly from February to July (https://www.marlin.ac.uk/species/detail/1386). It can be found on rocky substrata, from very exposed to very sheltered conditions (Bunker *et al.*, 2017); it flourishes in moderately exposed areas or in sites with strong current.

L. hyperborea is often found mixed with other kelp species, including *L. digitata* which may even be found growing on their stipes alongside various red seaweeds. The two species can be distinguished at low tide as *L. digitata* stipe and blade are bowed over while *L. hyperborea* remains erect.

As these two species grow in similar environmental conditions, a single table of suitable environmental ranges for growth has been prepared (Table 2.2).

a)  b) 

Figure 2.8 a) *Laminaria hyperborea* with inset closeup of holdfast; b) *Laminaria digitata* growing on a *Laminaria hyperborea* stipe. Found in drift material, Inch, Kerry, Ireland (photos credit: Gill Malin).

Table 2.2. Environmental thresholds for growth of *Laminaria hyperborea* and *Laminaria digitata*. SST = sea surface temperature; K_d = light attenuation coefficient; PAR = photosynthetic active radiation; TOxN = total oxidised nitrogen (nitrate+nitrite).

Environmental Factor	Optimal	Suboptimal	Unsuitable	Reference
Minimum SST (°C)	>5	2-5	<2	Kerrison *et al.*, 2015
Maximum SST (°C)	<16[#]	16-18	>18	Kerrison *et al.*, 2015
Minimum Salinity	>20	15-20	<15	Kerrison *et al.*, 2015
K_d(PAR) 10% light depth (m)	>2	1-2	<1	Same as *S. latissima*
Winter TOxN ($mmol/m^3$)	>10	4-10	<4	Broch and Slagstad, 2012; Kerrison *et al.*, 2015
Current ($m\ s^{-1}$)	0.1-1.5*		<0.1 & > 1.5	Kerrison *et al.*, 2015; Mooney-McAuley *et al.* 2016; Buck and Buchholz, 2005
Maximum wave height (m)	<6**		>6	Buck and Buchholz, 2005; Buck and Grote, 2018
Water depth (m)	>4***		<4	Mooney-McAuley *et al.,* 2016

[#]For *L. hyperborea*, optimal sea surface temperature is between 10-15°C (Bolton and Lüning, 1982).

* Optimal growth in high flow but can also be found in low flow environment (Kerrison *et al.*, 2015).

** There is some limited evidence that seaweed farms can withstand higher wave heights e.g. Ocean Rainforest in the Faroe Islands withstood a maximum significant wave height of 7-8 m (Buck and Grote, 2018).

*** Maximum depth will depend on the type and structure of the farm; for example, the Ocean Rainforest farm site has a water depth of 50-70 m; their cultivation rig can be deployed up to depths of 200 m (Bak *et al.*, 2018).

2.4. *Alaria esculenta*

Alaria esculenta, or winged kelp, has a spear-shaped frond with a distinct midrib throughout the length of the blade, and can grow up to 1.5 m (Figure 2.10). The colour can be yellowish, olive-green or rich brown (https://www.marlin.ac.uk/species/detail/1291). It is typically found in exposed and very exposed rocky shores, on western and northern coasts of the UK (Bunker *et al.*, 2017).

Thresholds for environmental variables for *A. esculenta* are given in Table 2.4. There were uncertainties associated with some thresholds which are discussed in the explanatory notes under Table 2.4.

Figure 2.10. *Alaria esculenta* (winged kelp) farmed in Scotland (photo credit: Elisa Capuzzo).

Table 2.4. Environmental thresholds for growth of *Alaria esculenta*. SST = sea surface temperature; K_d = light attenuation coefficient; PAR = photosynthetic active radiation; TOxN = total oxidised nitrogen (nitrate+nitrite).

Environmental Factor	Optimal	Suboptimal	Unsuitable	Reference
Minimum SST (°C)	>4	2-4	<2#	Tyler-Walters, 2008; Fredersdorf *et al.*, 2009
Maximum SST (°C)	<16	16-17	>17~	Sundene, 1962; Lüning, 1984
Minimum Salinity	>20	15-20	<15$	Karsten *et al.*, 2003; Fredersdorf *et al.*, 2009
K_d(PAR) 10% light depth (m)	>2	1-2	<1	Same as *S. latissima*
Winter TOxN (mmol/m^3)	>10	4-10	<4§	Not known, same as *S. latissima, L. digitata*
Current (m s^{-1})	0.1-1.5*		<0.1 & >1.5	Kerrison *et al.*, 2015; Mooney-McAuley *et al.*, 2016; Buck and Buchholz, 2005
Maximum wave height (m)	<6**		>6	Buck and Buchholz, 2005; Buck and Grote, 2018
Water depth (m)	>4***		<4	Mooney-McAuley *et al.*, 2016

Fredersdorf *et al.* (2009) reported that *A. esculenta* can tolerate temperatures of 4°C. This is broadly similar to the lowest optimal temperature for *S. latissima* and *L. digitata*, therefore the same threshold of 2°C for unsuitable minimum temperature was used.

~ This species optimal temperature is <16°C (Lüning, 1984). The limit of 17°C was estimated according to Birkett *et al.* (1998) who suggested to calculate lethal limit as 1-2°C above growth limit.

$ Fredersdorf *et al.* (2009) showed that *Alaria* tolerates salinity between 20 and 34. Karsten *et al.* (2003) observed limited changes to the photosynthetic capacity of Arctic *Alaria* between salinity 10 and 50. The threshold of 15 was chosen as an average value between the lowest salinities of these two studies.

§ The literature search did not provide relevant reference on optimal nutrient ranges for *Alaria*, hence the same ranges as *S. latissima* and *L. digitata* were used.

* Optimal growth in high flow and this species is naturally found in exposed areas.

** There is some limited evidence that seaweed farms can withstand higher wave heights e.g. Ocean Rainforest in the Faroe Islands withstood a maximum significant wave height of 7-8 m (Buck and Grote, 2018).

*** Maximum depth will depend on the type and structure of the farm; for example, the Ocean Rainforest farm site has a water depth of 50-70 m; their cultivation rig can be deployed up to depths of 200 m (Bak *et al.*, 2018).

2.5. Others brown seaweeds

There are other species of brown seaweeds which are not commercially farmed in the UK (or Europe) but have been the subject of farming trials, considering their ability to grow in warmer seas (e.g. *Sacchoriza polyschides*) or for reducing pressure on wild harvested stocks (e.g. *Fucus* spp.). This section is about horizon scanning of species which could be considered for cultivation in the medium-long term.

<u>Sacchoriza polyschides</u>

This kelp species, also known as Furbellows, generally grows up to 2 m but sometimes achieves 3 to 4 m (https://www.marlin.ac.uk/species/detail/1370). It occurs naturally on sand scour or stable mixed substrata, along the south coast of Britain, and the west coast of England and Scotland. It is a highly distinctive species with a flat belt-like stipe with frilled margins at the base and a large bulbous and warty holdfast (Figure 2.11). It grows fast and can opportunistically colonise available hard substrata and tolerate areas with stronger currents. This species is not currently commercially farmed in the UK, but trials have been carried out in Scotland (Kerrison *et al.* 2015 and references within), considering potential use of this species as biomass for biofuel production. *S. polyschides* is a high temperature ecotype which means it can grow at higher temperatures compared with *S. latissima* and *L. digitata* and is therefore recommended for areas were summer temperature exceeds 18°C (Kerrison *et al.*, 2015). On the other hand, it is less tolerant to changes in salinity (compared to the other kelps) and requires a minimum salinity of 33 (Kerrison *et al.*, 2015).

Figure 2.11. *Sacchoriza polyschides* growing opportunistically on the ropes of SAMS seaweed farm in Scotland (photo credit: Elisa Capuzzo).

Laminaria ochroleuca

Another warm-temperate seaweed species is *L. ochroleuca* or Golden Kelp. This kelp is very similar in morphology to *L. hyperborea* and can grow to 2 m tall (https://www.marlin.ac.uk/species/detail/1838). It is found naturally from Morocco to the south-west of England, which currently represents its northern limit, corresponding to a 10°C winter isotherm (Smale *et al.*, 2015 and reference within). There is evidence that this species is proliferating and expanding its range poleward in response to increased sea surface temperatures (Smale *et al.,* 2015).

L. ochroleuca is not commercially farmed in the UK and there is little/no information on its growth rates, chemical composition, and optimal environmental ranges for growth in the UK. However, in the longer-term, the increase of sea surface temperature due to climate change, potentially limiting growth of some kelp species while allowing other to spread, could make this species a candidate for cultivation.

***Fucus* species**

Seaweed species commonly known as Wracks and belonging to the *Fucus* genus (for example, *Fucus vesiculosus* and *Fucus spiralis*) are tough seaweeds, olive-green to brown in colour, occurring all around the British Isles from exposed rocky shores to saline lagoons (Bunker *et al.*, 2017). *Fucus* is normally harvested from wild stocks in the UK and (to our knowledge) there is no commercial cultivation of this species currently; however there have been cultivation trials in the Western Baltic Sea (Kiel Fjord) where natural stocks are limited and wild harvest is not permitted or viable (Meichssner *et al.*, 2020 and 2021). For details on cultivation methods and growth success we refer to the publications by Meichssner and colleagues. It is important to note that the method adopted for cultivation of *Fucus* is by “vegetative reproduction” i.e. fronds of *Fucus* were cut above the stipe from the wild and grown unattached in baskets in open water. After a growth period the fronds were harvested and some of them were used as seedlings for the next growing season. *Fucus* is primarily an intertidal genus and can tolerate regular desiccation by air exposure; an experimental trial of *Fucus* cultivation showed that frequent mild desiccation does not negatively impact growth rates, but it is an effective way to control biofouling by other organisms therefore resulting in cleaner *Fucus* biomass (Meichssner *et al.*, 2021).

Figure 2.12. *Fucus* spp. growing on rocks (photo credit: Elisa Capuzzo).

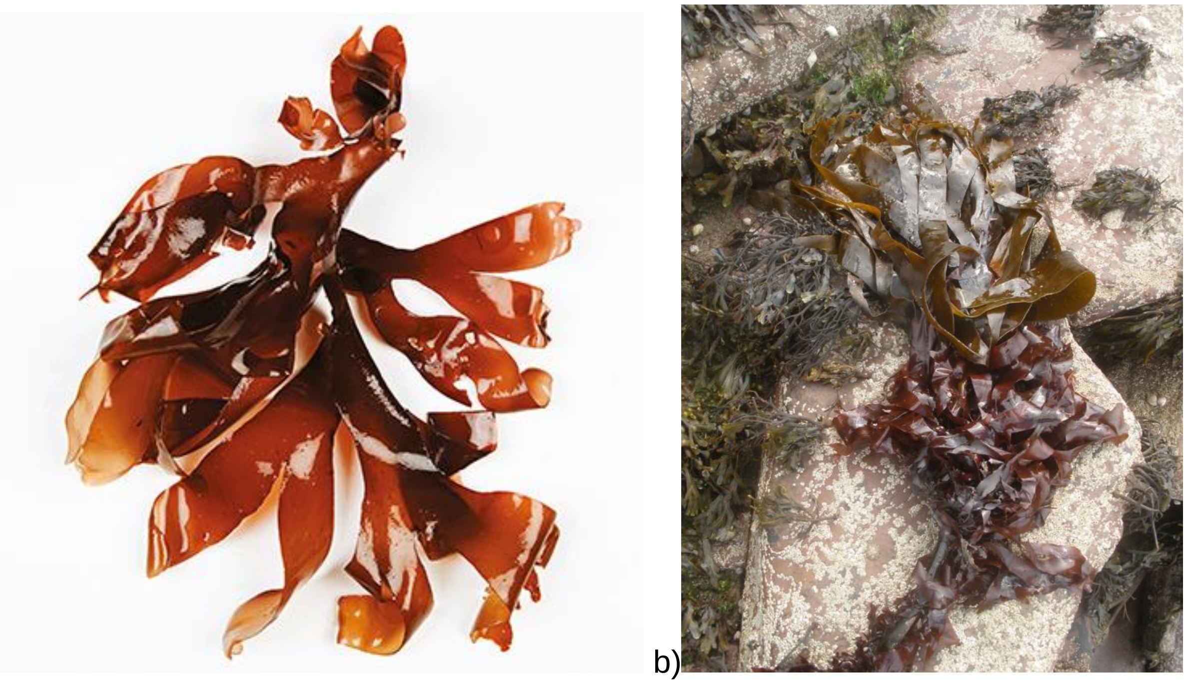
3. Red seaweeds

Red seaweeds (Rhodophyta) are the most diverse group of seaweeds with up to 7,000 species worldwide and over 350 found around the British Isles. They are the oldest known seaweed group on Earth (Bunker *et al.,* 2017).

Most of these seaweeds are small and delicate although species such as *Palmaria palmata* can grow up to 0.5 m long. The characteristic red/purple colour comes from phycoerythrin and phycocyanin pigments present in the thalli. The cell wall is formed by material such as agar and carrageenan, products which represent a multi-billion-dollar industry globally. They have very complex life history which makes them challenging to cultivate (see example provided below; Bunker *et al.,* 2017).

3.1. *Palmaria palmata*

Palmaria palmata, or dulse, is a flat red seaweed, which can have either a simple blade (with/without marginal proliferations) or branches, and can have a leathery texture (Bunker *et al.*, 2017; Figure 3.1). Dulse has a purplish or brownish-red colour and grows on rocks or as an epiphyte on stipes of other seaweed species (e.g. Forest Kelp, *L. hyperborea*), in sheltered or moderately exposed areas (Werner and Dring, 2011; Bunker *et al.*, 2017).



a) b)

Figure 3.1. a) *Palmaria palmata* (dulse) from the Cornish coast (photo credit: the Cornish Seaweed Company); b) *P. palmata* growing on a *Laminaria hyperborea* stipe, found in drift material, Inch, Kerry, Ireland (photo credit: Gill Malin).

It presents an unusual and complex life history (even for a seaweed; Figure 3.2). Females and males develop separately, and the larger thalli (the entire body of the seaweed) found on shores are either male or have sporangia (structures that release spores). Female plants reach maturity when < 1 mm in size and are overgrown by the sporophytes, after fertilization (Bunker *et al.*, 2017). We refer the reader to the review by Stévant *et al.* (2023) for a detailed description of the life cycle of *P. palmata*.

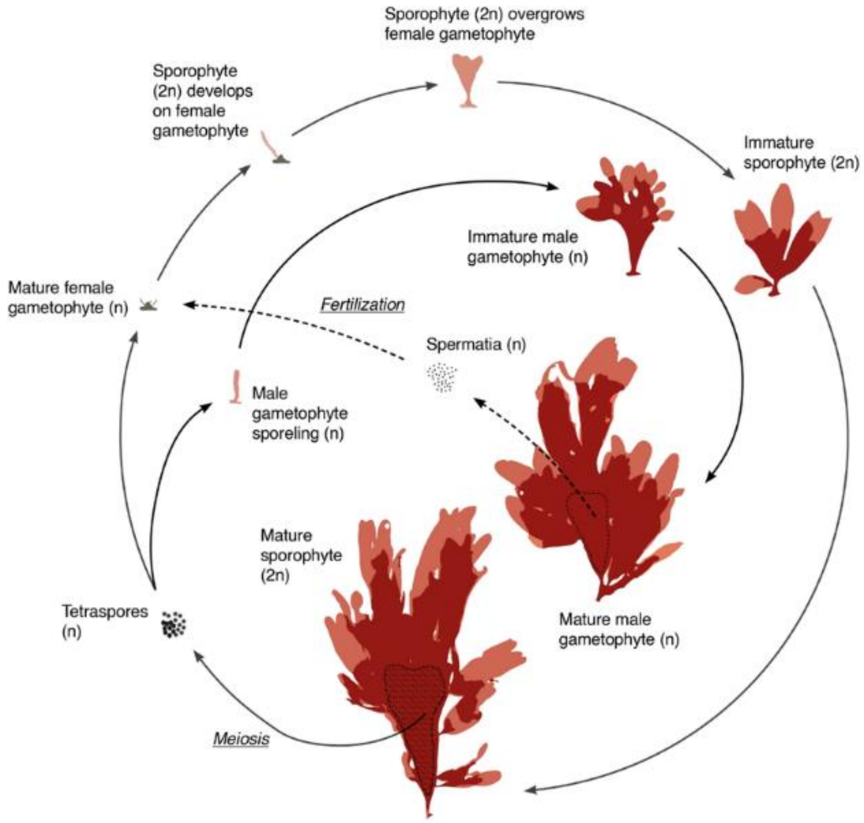


Figure 3.2 Life cycle of *Palmaria palmata*. The dashed-line areas on mature sporophytes (with dotted fill) and gametophyte fronds indicate tetrasporangial (sorus) and spermatangial tissues respectively (from Stévant *et al.*, 2023).

Cultivation of dulse presents multiple bottlenecks such as low rates of spore release and germination, high mortality, and epibiont contamination, highlighting the need for optimisation of hatchery methods (Stévant *et al.*, 2023). In terms of environmental conditions, temperature is a critical factor affecting photosynthetic performance, growth and reproduction (Stévant *et al.*, 2023).

Palmaria palmata can be cultivated in tanks (controlled conditions in land-based facilities) or at sea, in open waters, seeded on substrates (such as twine or nets) or on cultivation rigs (Stévant *et al.*, 2023). Detailed information on both type of cultivation can be found in the reviews by Grote (2017) and Stévant *et al.* (2023). Grote (2017) highlighted the importance of irradiance and frequent seawater exchange to ensure a sufficient supply of nutrients and carbon dioxide, while for open-water farming, the site selection and farm system design are important elements to consider. Stévant *et al.* (2023) summarised the different methods and conditions for farming dulse since 1980 in a useful infographic (Figure 3.3).

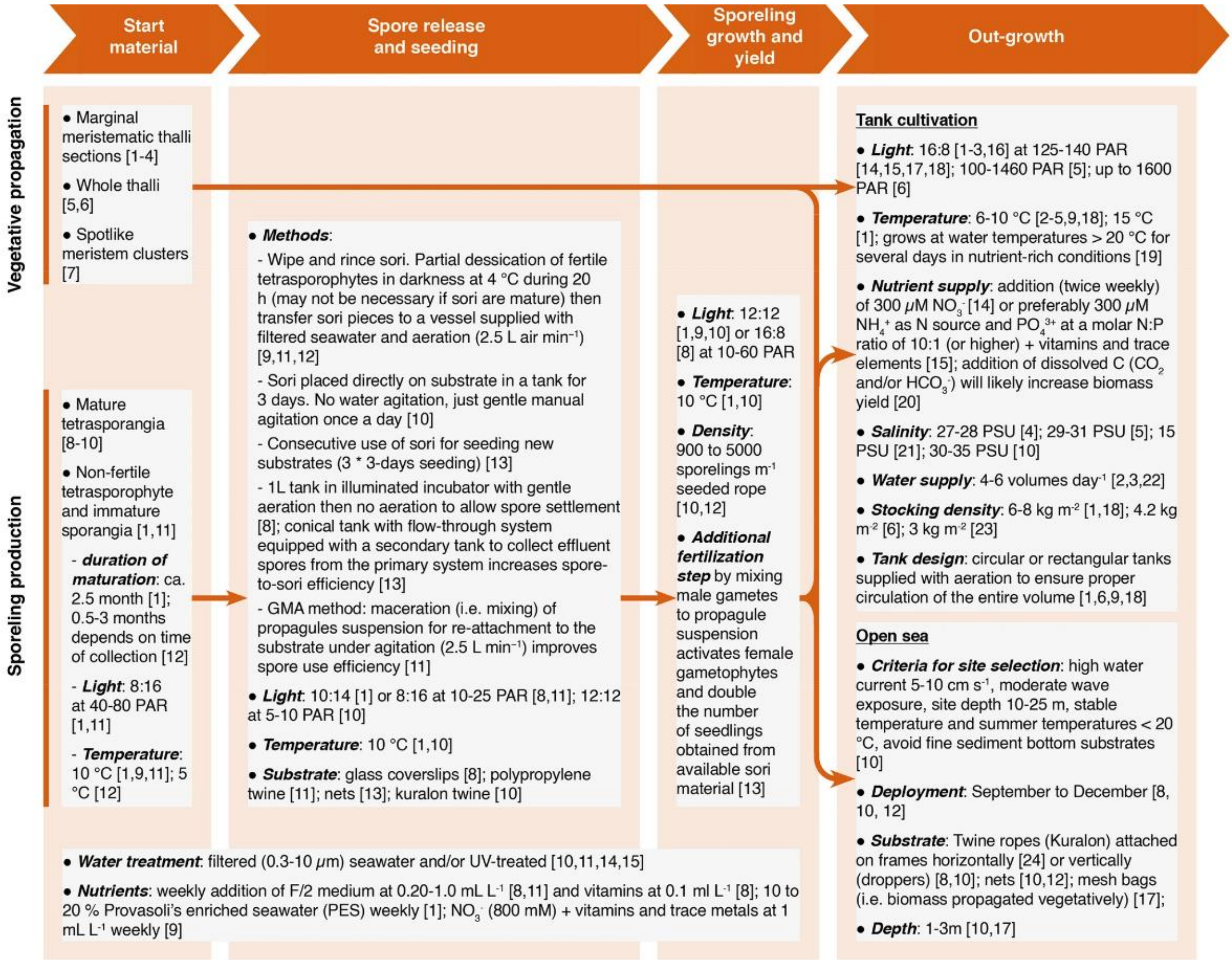


Figure 3.3 Overview of different methods and optimal conditions for cultivation of *Palmaria palmata* based on published studies from the 1980s from Stévant *et al.* (2023). We refer the reader to the review by these authors for details of the references cited in the figure.

Environmental ranges for growth of *Palmaria palmata* are given in Table 3.1.

Table 3.1 Environmental thresholds for growth of *Palmaria palmata*. SST = sea surface temperature; Kd = light attenuation coefficient; PAR = photosynthetic active radiation; TOxN = total oxidised nitrogen (nitrate+nitrite).

Environmental Factor	Optimal	Suboptimal	Unsuitable	Reference
Minimum SST (°C)	>6	2-6	<2[#]	Morgan and Simpson, 1981; Werner and Dring, 2011
Maximum SST (°C)	<15	15-17	>17	Morgan and Simpson, 1981; Werner and Dring, 2011 Grote, 2018
Minimum Salinity	>32	30-32	<30[~]	Morgan and Simpson, 1981; Hill, 2008
K_d(PAR) 10% light depth (m)	>1	0.5-1	<0.5	Estimated this study[$]
Winter TOxN (mmol/m^3)	>10	4-10	<4	Estimated this study[§]
Current (m s^{-1})	0.1-1.5*		<0.1 & >1.5	Kerrison *et al.*, 2015; Mooney-McAuley *et al.*, 2016; Buck and Buchholz, 2005
Maximum wave height (m)	<6**		>6	Buck and Buchholz, 2005; Buck and Grote, 2018
Water depth (m)	>4***		<4	Mooney-McAuley *et al.*, 2016

[#] Morgan and Simpson (1981) tested that *P. palmata* grows well between 6°C and 14°C but poorly at 18°C, while Werner and Dring (2011) identified the optimal temperature range between 8°C and 12°C, with limited growth above 15°C. At the same time the latter authors indicated that winter temperature (above ice-formation) is not considered damaging. So, the limit of 2°C was chosen for consistency with *L. digitata* and *L. hyperborea*, noting also that *P. palmata* can be an epiphyte of these kelp species.

[~] *P. palmata* presents stenohaline features, as it is a typical sublittoral red alga, adapted to full, stable salinity. Werner and Dring (2011) recommend avoiding cultivation in brackish water and estuaries; in fact, this species presented high mortality at a salinity of 15 (Karsten *et al.*, 2003). Morgan *et al.* (1980) reported that 32 is the optimal salinity for *P. palmata*. Interestingly, Schmedes and Nielsen (2020b) observed that dulse from Danish inner-waters was maximal at salinity of 15 highlighting occurrence of *P. palmata* ecotypes adapted to a wide range of salinity conditions. Based on this information an unsuitable salinity level of 30 was assumed allowing 2 points of salinity tolerance between an unsuitable level and the optimal value of 32.

[$] This species lives in natural shaded canopy of kelp blades, so high light intensity in summer can cause bleaching; when farmed, it may be necessary to lower the algae deeper in the water column (Werner and Dring, 2011). Edwards (2007) showed that in culture conditions and under nitrogen depletion, bleaching of *P. palmata* fronds occurs at irradiance levels above 200 µmol photons m^{-2} s^{-1} PAR after 2–3 weeks. Based on this consideration, it was assumed that this species can live in more turbid waters than the other seaweed species considered in this study and therefore the threshold levels are lower than those for the other seaweed species.

§ Not known, so assumed the same as for *L. digitata* and *L. hyperborea*.

* Found in both sheltered and moderately exposed sites.

** There is some limited evidence that seaweed farms can withstand higher wave heights e.g. Ocean Rainforest in the Faroe Islands withstood a maximum significant wave height of 7-8 m (Buck and Grote, 2018).

*** Maximum depth will depend on the type and structure of the farm; for example, the Ocean Rainforest farm site has a water depth of 50-70 m; their cultivation rig can be deployed up to depths of 200 m (Bak *et al.*, 2018).

3.2. *Porphyra* spp.

The genus *Porphyra*, also commonly known as Laver, include several species such as *P. dioica* (Black Laver), and *P. umbilicalis* (Tough Laver or Purple Laver; Bunker *et al.*, 2017; Figure 3.4; https://www.marlin.ac.uk/species/detail/1463). Laver has a very thin foliose membranous blade, one cell layer thick but tough, a very short stipe and a discoidal holdfast. The irregularly shaped fronds can be lanceolate or broad and ovoid in shape (Lavik, 2016), with a dark reddish-brown colour, grading to olive-green (Bunker *et al.*, 2017). *P. umbilicalis* is < 20 cm long/wide while *P. dioica* can reach up to 1 m in length.

It can be found on bedrock, boulders, and other substrata (e.g. barnacles, other seaweeds) throughout the shore but mainly in the upper littoral (Bunker *et al.*, 2017), where they can resist desiccation.

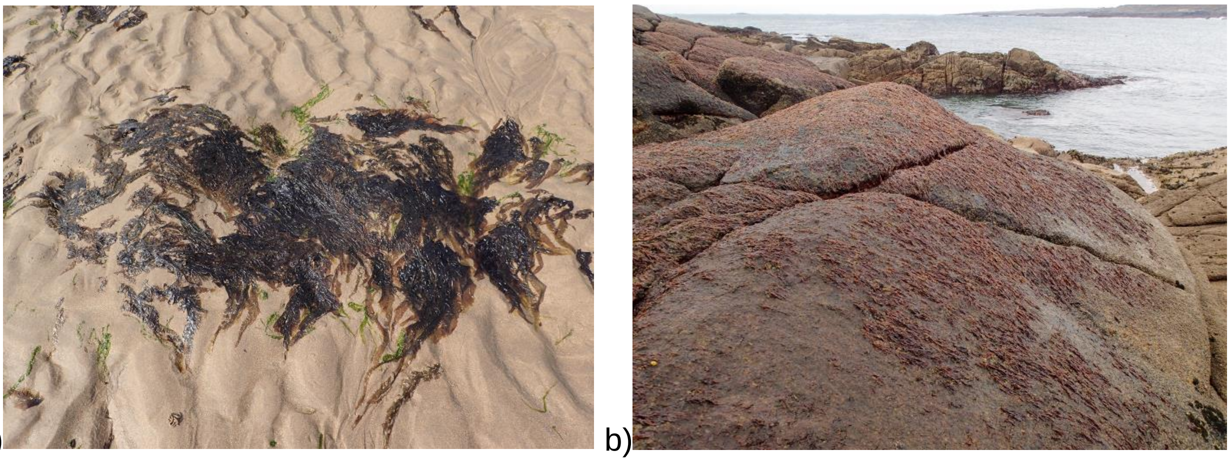
a) b)


Figure 3.4 a) *Porphyra dioica* and b) *Porphyra umbilicalis* (photo credits: Francis Bunker @MarineSeen).

In the UK, Laver is harvested from the wild as a food source to produce laverbread and other food products, while in countries such as Japan, South Korea and China species of *Pyropia* (belonging to the same group of bladed Bangiales as *Porphyra*) are cultivated and processed into nori sheets for sushi (Knoop *et al.*, 2020). Not only does this species retains a high market value, but it also has a high nutrient uptake rate, suitable for integration with other forms of aquaculture (Integrated Multi-trophic Aquaculture). In the British Isles, *P. dioica* is found year-round making it a promising candidate for cultivation (Knoop *et al.*, 2020).

To date, the cultivation of *Porphyra* spp. remains a challenge due to uncertainty regarding elements of the species' heteromorphic life cycle. The process has been successfully established for the Asian species (*Pyropia*), and useful overviews of the cultivation of this species are provided on the Seaweed Insights (https://seaweedinsights.com/farm-design-pyropia/), FAO (https://www.fao.org/fishery/en/culturedspecies/porphyra_spp/en) websites or the New England Seaweed Culture Handbook-Nursery Systems (Redmond *et al.*, 2016). However, cultivation has yet to be fully understood in the European species (*Porphyra*), therefore limiting potential for large scale production.

The complex sexual life cycle (see Figure 3.5) alternates between the bladed gametophytes and the microscopic sporophytes (also called the conchocelis phase). Male gametes fertilise female gametes resulting in sporangia, which in turns release spores. Once the spores settle on a suitable substrate (mollusc shells) they germinate into the conchocelis. The latter release conchospores which germinate into the edible thallus (Knoop *et al.*, 2020 and reference within).

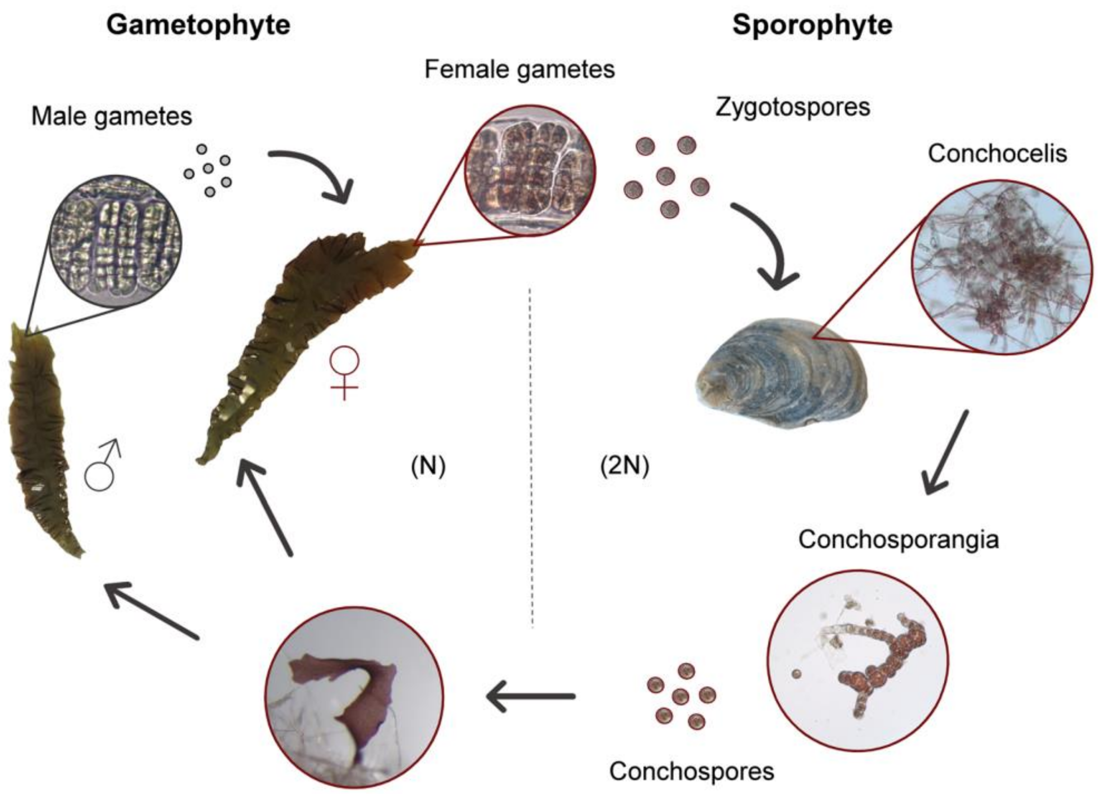


Figure 3.5 The heteromorphic sexual life cycle of *Porphyra*, highlighting the two phases: as a macroscopic thallus (gametophyte), and microscopic conchocelis (sporophytes), from Knoop *et al.* (2020).

Farming starts with the culture of conchocelis in tanks on land with a layer of calciferous shells at the bottom for the conchochelis to attach to. The release of conchospores is controlled by changes in light and temperature; the conchospores are then seeded on floating nets and transported to a nursery site in the sea where the gametophytes will develop. In the sea, the nets are regularly exposed out of the water (e.g. mechanically or with tide variations) to inhibit growth of fouling organisms. When blades are 2-3 mm long the nets are transferred to a larger farm site for further growth (see review by Lavik, 2016 and reference within).

The mass release of conchospores is a critical stage of cultivation and has been identified as the bottleneck for farming of *Porphyra* in the wider European area. Specific environmental conditions, such as length of the photoperiod and temperature, has been observed to be particularly important for the development of the conchocelis phase (Knoop *et al.*, 2020). For *P. dioica*, a short photoperiod with high temperature resulted in highest germination success of spores while long photoperiods at 18°C promoted conchocelis growth (Knoop *et al.*, 2020). Furthermore, experiments showed that mass release of conchospores was triggered by a drop in temperature (from 15°C to 9°C) and a short photoperiod (Knoop *et al.*, 2020).

In terms of suitable environmental conditions for development of the gametophyte when in open waters, studies carried out on *P. umbilicalis* in New England and on the Northwest Atlantic coast, showed that optimal growth temperature was between 10°C and 15°C, with light levels ≥110 µmol photons m^{-2} s^{-1} and ≥12 hours of light in a day according to Green and Neefus (2016) and between 8-10°C for Redmond and co-authors (2016). Growing *P. umbilicalis* under low light (≤ 60 µmol photons m^{-2} s^{-1}), and neutral/long day conditions resulted in higher pigment content, but also in higher protein content, making the blades more suitable for an aquaculture feed substitute or food product (Green and Neefus, 2016).

3.3. *Osmundea pinnatifida*

Osmundea pinnatifida or Pepper Dulse is commonest of the Flat fern-weeds (Bunker *et al.*, 2017; Figure 3.6). It grows up to 8 cm in length, and the thalli are cartilaginous and tough. It varies in colour from purple to brownish-red although size and coloration depend on its location along the shore; for example, higher on the shore with higher exposure by the tide resulted in smaller yellow-green plants while plants living lower on the shore present a reddish-brown colouration (https://www.marlin.ac.uk/species/detail/1455; Silva and Pereira, 2020). It thrives on open rock surfaces, in a range of shores from moderately sheltered to exposed.

Figure 3.6 *Osmundea pinnatifida* (photo credit: Francis Bunker @MarineSeen).

It has a slightly spicy taste that resembles mussels, crabs or truffles and therefore it has a great potential for gastronomic use; however, there is currently no commercial farming of this species, due to being a light-sensitive seaweed and its slow growth (Silva and Pereira, 2020).

As observed for the other red seaweeds considered in this chapter, it has a complex life cycle. *O. pinnatifida* presents three phases, including the gametophyte (female and male), the carposporophyte and tetrasporophyte; the gametophytes and tetrasporophytes are similar (isomorphic; Figure 3.7).

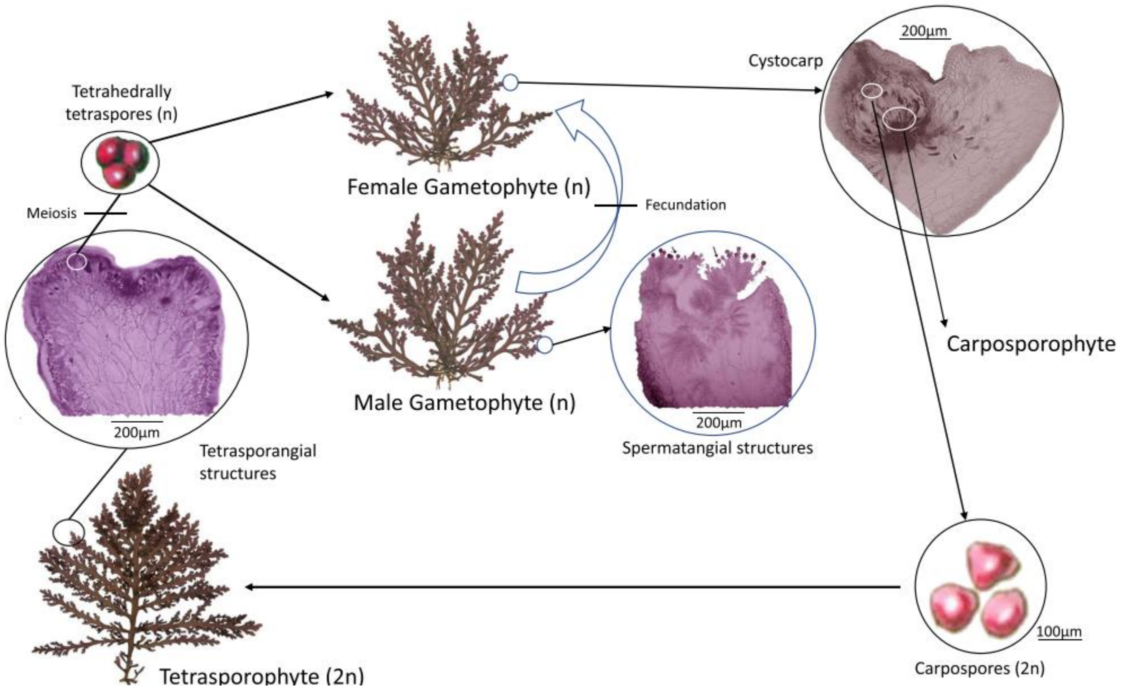


Figure 3.7 Life cycle of *Osmundea pinnatifida* highlighting the three main phases (gametophytes, carposporophyte and tetrasporophyte; from Silva and Pereira, 2020).

In terms of farming trials, Silva and Pereira (2020) provide some examples carried out in Portugal, which had unsatisfactory results. On the contrary, Biancacci (2019) succeeded in investigating the reproductive cycle and juvenile production from mature tetrasporophytes cultivated in tanks. Biancacci's highly informative thesis describes trials of cultivation in indoor and outdoor tumbling systems and with different media. Cultivation in the tumbling system allowed for continuous monitoring of parameters and continuous exchange of nutrients, sufficient aeration and distribution of light. Pepper dulse was cultivated at sea surface temperatures between 10-14°C, as temperatures > 15°C resulted in algae die off. Silva and Pereira (2020 and references) also observed that this species is found more frequently at sea surface temperatures between 10-15°C (although it has been found at ranges between 5-25°C) and salinities between 30 to 35.

Cultivation outdoors has proven to be more promising than cultivation indoors with lower management costs. The low success of indoor tanks might be due to the shape and colour of the tanks affecting the light field available to the seaweed (Biancacci, 2019). In the outdoor tanks, growth was negatively affected by low water exchange and grazers.

4. Green seaweeds

Green algae are classified as plants; the colour green is the result of chlorophyll a and b, which are pigments found also in land plants. There are around 110 species of green seaweeds in the British Isles with a variety of sizes. Some green seaweeds such as *Ulva* (sea lettuce) can become extremely abundant resulting in green tides (Bunker *et al.,* 2017).

They grow attached to a variety of substrata, including rocks, and man-made structures, although some species also live as floating populations.

Thanks to their unique elemental composition, nutritional profile and organoleptic properties, green algae have been adopted for various applications including biorefinery operations, land-based integrated multitrophic aquaculture (IMTA) and high-value food products (see review by Moreira *et al*., 2020).

4.1. *Ulva spp.*

Ulva species are also known sea lettuces or gut weeds. Their fronds can be flat fluted or toothed and they are formed by two cell layers. They attach by a basal disc and rhizoids, but they can also be free-floating. The size of the frond varies between 2 and 70 cm long but can reach as much as 100 cm or more in *Ulva lactuca* (Bunker *et al.,* 2017). There are five species of sea lettuce in Britain but due to their variable shape they can be quite difficult to identify to species level, therefore molecular analysis may be required to determine the species (Bunker *et al.,* 2017).

The blades are delicate to tough, and dark green in colour (Figure 4.1). *Ulva* species can be found in a variety of habitats; for example, *U. lactuca* can be found on rocks, or growing on other algae, in fully marine or brackish environments, mostly on the shore but can also be subtidal down to at least 15 m depth (Bunker *et al.* 2017).

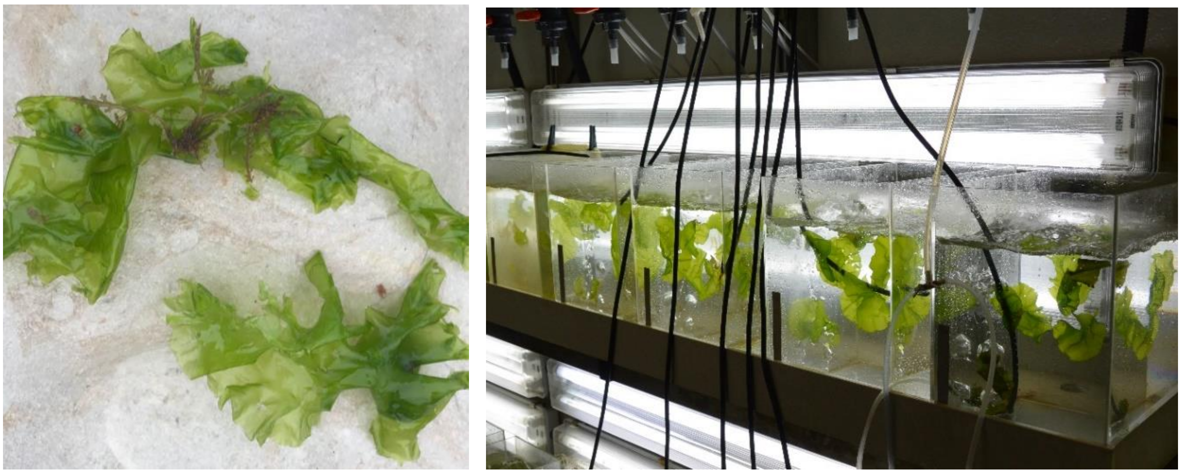


Figure 4.1 Example of *Ulva* spp., washed up on the shore and cultivated in a laboratory (photo credits: Elisa Capuzzo).

Ulva has a complex life cycle where both the gametophyte (that reproduces sexually) and the sporophyte (which reproduces asexually) look the same (isomorphic; Figure 4.2). The sporophyte produces microscopic zoospores (each one with four flagella); these can be sometimes liberated in large numbers turning the sea of a green colour. The zoospores settle within an hour of being liberated and germinate into the gametophyte, which in turn will grow to produce microscopic gametes each with two flagellae. Two gametes fuse to produce a zygote which will then grow into a sporophyte (Bunker *et al.,* 2017). However, *Ulva* can also reproduce by fragmentation when part of the thallus is broken off.

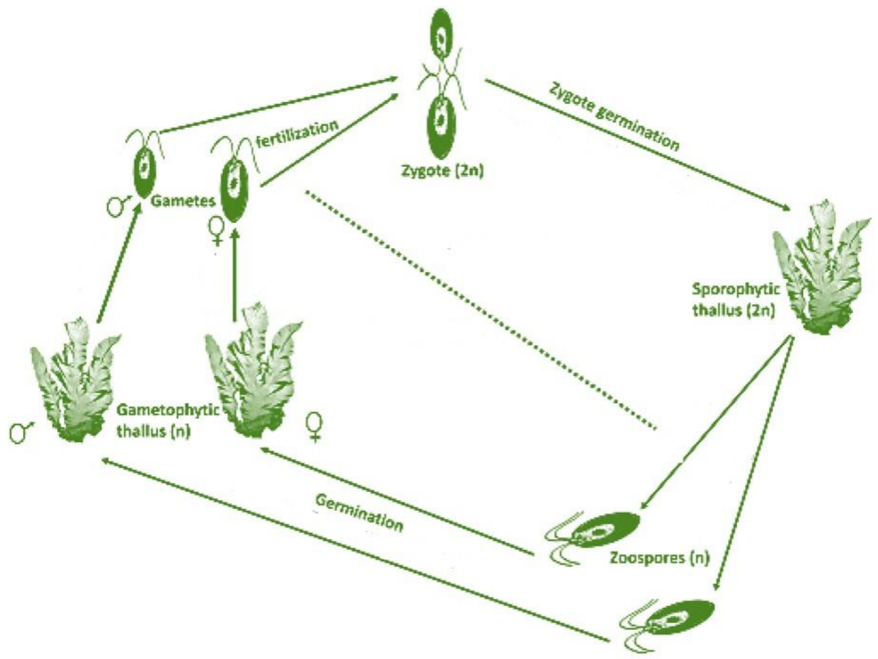


Figure 4.2 Life cycle of *Ulva* spp. (modified from Baweja *et al*., 2016).

Cultivation of *Ulva* largely depends on the ability to produce seed stock and two main methods can be adopted to obtain viable propagules (also called seedlings): asexual propagation or sexual reproduction via gamete conjugation (Moreira *et al*., 2020). Asexual propagation has relative advantages opposed to sexual reproduction as it does not require manipulation of the entire sexual life cycle, allowing for simpler cultivation technologies.

Artificial propagation of *Ulva* can be achieved by inducing the release and germination of swarmers from thalli; swarmer refers to motile zoospores or gametes originating from the sporophytes or the gametophyte, respectively. In addition, *Ulva* can also regenerate from fragmented tissue (Moreira *et al*., 2020). We refer the reader to the EU COST Action SeaWheat group (https://seawheatcost.haifa.ac.il/) for access to multiple publications, videos and opportunity to participate to training schools on *Ulva* propagation and cultivation.

Once the propagules have reached a suitable size, they can be transplanted to cultivation grounds or systems (e.g. tanks, raceways) or at sea in open waters on an artificial substratum (ropes, nets etc.), in calm oceanic or estuarine waters. *Ulva* can also be cultivated free-floating in tanks (where propagules settle on wheel-shaped bio-balls), by using drip-irrigation systems, or in pilot scale photobioreactors (see the extensive review by Moreira *et al*., 2020 for further details and references).

Most of *Ulva* cultivation in Europe is land-based or near-shore based, in tanks, ponds, bioreactors, or basins (see review by Steinhagen *et al*., 2022). Land-based cultivation allows for full control of cultivation parameters, easy access to biomass, and constant production, however it has high costs of construction, operation and maintenance. On the other hand, sea-based cultivation enables low production costs but biofouling pressure, seawater temperature and irradiance can be difficult to manage as they are strongly season-dependent (Steinhagen *et al*., 2022). For example, cultivation at sea has been tested by Steinhagen and co-authors (2021, 2022) on the Swedish west coast within the Skagerrak region of the North Sea (Figure 4.3); the site had a depth of 10 m with tidal excursion of 2 m; *Ulva* was cultivated on longlines suspended at 1.5 m below the surface, and 4 m apart.

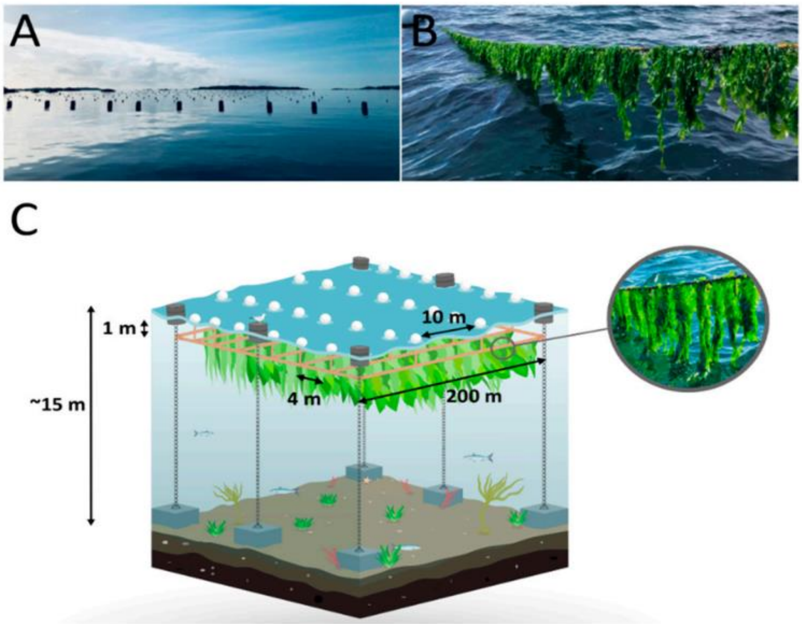


Figure 4.3 Offshore cultivation site for *Ulva fenestrata*, located in the Koster archipelago, Skagerrak (Sweden). The nylon twine with juvenile seaweeds was coiled around longlines (200 m long), which were attached to buoys anchored to the seafloor. Ropes were suspended 1.5 m below the surface, 4 m apart (from Steinhagen *et al*., 2021).

Salinity is one of the most important environmental factors influencing *Ulva*. As sea lettuce lives in the intertidal zone it can tolerate a wide range of salinity (euryhaline) as well as of temperatures. Lüning (1984) tested tolerance to temperature of dominant species near Helgoland and demonstrated that *Ulva lactuca* can tolerate temperatures between 0°C and 28°C (alive with measurable photosynthesis). Bruhn *et al*. (2011) cultivated *Ulva lactuca* at temperatures between 7 and 23°C and salinity between 25 and 28.5, while Steinhagen *et al*. (2021) cultivated *Ulva fenestrata* at a sheltered open-water site off the Koster archipelago (Skagerrak) with mean temperature of 7°C and salinity 27.6, between October to May.

Ammonium is the preferential N-source for *Ulva*, compared to nitrate; in fact, ammonium can be assimilated directly by algae into aminoacids (Ghaderiardakani *et al*., 2019). For example, Ale and co-authors (2011) showed that *Ulva lactuca* farmed in an ammonium nutrient rich medium (50 μM of nitrogen) accelerated growth rates to a maximum of 16.4% d^{-1}. Because of this ability of taking up nitrogen (particularly ammonium), there are multiple examples of *Ulva* adopted as biofilters in IMTA settings with other organisms (e.g. abalone, sea urchin, seabream; Moreira *et al*., 2020 and references). The cultivation of *Ulva* in IMTA settings has the double benefit of increasing water quality and of providing a feed for other trophic levels (e.g. abalone).

5. Considerations and recommendations

This report aimed to review seaweed species and farming methods currently adopted in the UK and in Europe, to support the development and scaling-up of the seaweed industry in Norfolk. In addition, the review reported suitable environmental ranges for farming different species of brown, red and green seaweeds.

The environmental ranges for optimal, suboptimal and unsuitable growth for *S. latissima*, *L. hyperborea*, *L. digitata*, *A. esculenta* and *P. palmaria*, described in this report, have then been used to determine suitable areas for cultivation off the Norfolk coast, as well as co-location opportunities with offshore wind farms. The resulting maps can be accessed through the SEA project website, together with all the other reports and outputs from the project (https://hethelinnovation.com/seaweed-in-east-anglia/).

As the seaweed industry in the UK is still at a nascent or early stage, information available on cultivation of species and methods for the UK were limited, therefore the review included references based on cultivation in Europe and north-west America (where species and environmental conditions were considered comparable).

Information on potential presence of pests and diseases were also limited to cultivation in the UK and Europe, due to the smaller scale of the industry, compared for example with Asian countries. With the scaling-up of the seaweed industry it will be essential to consider effective biosecurity measures to avoid introduction of non-indigenous species, to contain potential pest and disease outbreaks, and to conserve genetic diversity (Cottier-Cook *et al*., 2021).

The information provided in this review should be considered as "*guidelines*" for prospective seaweeds farmers; information given (for example on environmental thresholds) should be critically reviewed against the local conditions at the farm site, farming method adopted, facilities and vessel available.

Five main limitations and associated recommendations emerged from this review, which are listed in Table 5.1. Addressing these limitations would not only support the development of a seaweed industry in Norfolk but more widely in the UK.

Table 5.1 Limitation and associated recommendations (actions) identified in this report.

Limitations	Recommendation
Seaweed species – only a few seaweed species (mainly brown seaweeds) are currently successfully farmed; other potentially interesting species (e.g. for food) such as a laver are not currently commercially farmed due to uncertainty around life cycles.	Need for Research & Development around cultivation of these other potential species.
Environmental conditions – there is a high level of uncertainty around optimal, suboptimal and unsuitable ranges for some of the environmental variables considered, particularly current and wave height, due to limited/lack of observations. Furthermore, ranges depend on the farming method and farm configuration.	Collection and sharing of data on environmental conditions occurring at existing farms in the UK.
Farming methods – there are multiple techniques adopted for farming (longline, droppers, grids, etc.), different substrata to grow seaweed (twine, materials, mesh) with or without bio-binder, used across the UK. Methods are chosen to suit location, farm size, yield, species farmed, end use and environmental conditions – one method does not fit all locations.	Detailed information on farm structure and farming methods collected and shared; increase knowledge sharing between farmers.
Protocols / guidelines – there is a good body of freely available 'grey literature' (e.g. reports, guidelines, tutorials, videos), in addition to courses with fees. These provide information on e.g. how to collect fertile material, nursery set up and outplanting/farming at sea, although mainly for brown seaweeds. It may be difficult to keep track of these resources and the weblinks may stop working.	Development of a centralised platform / repository where all these references can be found.
Licence registers – it is very challenging to trace all the existing marine licences for seaweed aquaculture in the UK across the four registers. Because of this, it is difficult to gauge the development of the aquaculture industry.	Collection of information on seaweed licence and production (e.g. species, yields) recorded nationally.

References

Ale, M.T., Mikkelsen, J.D., Meyer, A.S. (2011). Differential growth response of *Ulva lactuca* to ammonium and nitrate assimilation. Journal of Applied Phycology 23, 345–351. https://doi.org/10.1007/s10811-010-9546-2

Araújo, R., Vázquez Calderón, F., Sánchez López, J., *et al*. (2021). Current status of the algae production industry in Europe: an emerging sector of the blue bioeconomy. Frontiers in Marine Science 7, 626389. https://doi.org/10.3389/fmars.2020.626389

Bak U.G., Mols-Mortensen A., Gregersen O. (2018). Production method and cost of commercial-scale offshore cultivation of kelp in the Faroe Islands using multiple partial harvesting. Algal Research 33, 36-47, https://doi.org/10.1016/j.algal.2018.05.001

Barbier, M., Charrier, B., Araujo, R., Holdt, S.L., Jacquemin, B., Rebours, C. (2019). PEGASUS -PHYCOMORPH European Guidelines for a Sustainable Aquaculture of Seaweeds, COST Action FA1406 (M. Barbier and B. Charrier, Eds), Roscoff, France.

Baweja, P., Kumar, S., Sahoo, D., Levine, I. (2016). Chapter 3 - Biology of Seaweeds, Editor(s): Joël Fleurence, Ira Levine, Seaweed in Health and Disease Prevention, Academic Press 41-106. https://doi.org/10.1016/B978-0-12-802772-1.00003-8.

Biancacci, C. (2019). Towards a sustainable production of *Osmundea pinnatifida*: insight into the cultivation and biochemical composition of the species. Doctor of Philosophy thesis, University of Aberdeen, pp. 374 (https://pureadmin.uhi.ac.uk/ws/portalfiles/portal/13957667/Cecilia_Biancacci_thesis.pdf).

Birkett, D.A., Maggs, C.A., Dring, M.J., Boaden, P.J.S., Seed, R. (1998). Infralittoral reef biotopes with kelp species (volume VII). An overview of dynamic and sensitivity characteristics for conservation management of marine SACs. Scotttish Association of Marine Science (UK Marine SACs Project), pp.174.

Bolton, J. J., Lüning, K. (1982). Optimal growth and maximal survival temperatures of Atlantic Laminaria species (Phaeophyta) in culture. Marine Biology 66, 89–94. https://doi.org/10.1007/bf00397259.

Broch, O.J., Slagstad, D. (2012). Modelling seasonal growth and composition of the kelp *Saccharina latissima*. Journal of Applied Phycology 24, 759–776. https://doi.org/10.1007/s10811-011-9695-y

Bruhn, A., Dahl, J., Nielsen, H.B. *et al*. (2011). Bioenergy potential of *Ulva lactuca*: Biomass yield, methane production and combustion, Bioresource Technology 102(3), 2595-2604. https://doi.org/10.1016/j.biortech.2010.10.010.

Buck, B. H., Grote, B. (2018). Seaweed in high-energy environments. Protocol to move *Saccharina* cultivation offshore. In Charrier, B., Wichard, T. and Reddy, C.R.K. (Eds) Protocols for Macroalgae Research. CRC Press, pp. 485.

Buck, B.H., Buchholz, C.M. (2005). Response of offshore cultivated *Laminaria saccharina* to hydrodynamic forcing in the North Sea. Aquaculture 250, 674-691. https://doi.org/10.1016/j.aquaculture.2005.04.062

Buckley, S., Hardy, K., Hallgren, F. *et al*. (2023). Human consumption of seaweed and freshwater aquatic plants in ancient Europe. Nature Communications 14, 6192. https://doi.org/10.1038/s41467-023-41671-2

Bunker, F.StP.D., Maggs, C.A., Brodie, J.A., Bunker, A.R. (2017). Seaweeds of Britain and Ireland. Second edition. Wild Nature Press, Plymouth, UK.

Campbell, I., Macleod, A., Sahlmann, C., Neves, L., Funderud, J., Øverland, M., Hughes, A.D., Stanley, M. (2019). The Environmental Risks Associated With the Development of Seaweed Farming in Europe - Prioritizing Key Knowledge Gaps. Frontiers in Marine Science 6:107. doi:10.3389/fmars.2019.00107

Capuzzo, E. (2022). Seaweed Industries and Products in the UK: A Brief Review. In: Ranga Rao, A., Ravishankar, G.A. (eds) Sustainable Global Resources Of Seaweeds Volume 1. Springer, Cham. https://doi.org/10.1007/978-3-030-91955-9_14

Capuzzo, E., Collingridge, K., Mitchell, P., Aldridge, J. (2018). Feasibility study: areas suitable for seaweed growth and farming around the English Coast. Cefas Contract Report C7677.

Capuzzo, E., Stephens, D., Aldridge, J., Forster, R.M. (2014). Feasibility study – Potential locations for macro-algae farming off the East Anglian coast, The Crown Estate, pp. 37.

Corrigan, S., Brown, A.R., Tyler, C.R., Wilding, C., Daniels, C., Ashton, I.G.C., Smale, D.A. (2023). Development and Diversity of Epibiont Assemblages on Cultivated Sugar Kelp (*Saccharina latissima*) in Relation to Farming Schedules and Harvesting Techniques. Life 13, 209. https://doi.org/10.3390/life13010209

Cottier-Cook, E.J., Nagabhatla, N., Asri, A., *et al*. (2021). Ensuring the sustainable future of the rapidly expanding global seaweed aquaculture industry – a vision. United Nations University Institute on Comparative Regional Integration Studies and Scottish Association for Marine Science Policy Brief. ISBN 978-92-808-9135-5

Edwards, M.D. (2007). The cultivation of the edible red alga, *Palmaria palmata* for aquaculture. PhD thesis, The Queen's University of Belfast (QUB), Belfast, UK.

Edwards, M., Watson, L. (2011). Aquaculture Explained #26. Cultivating *Laminaria digitata*. Bord Iascaigh Mhara (BIM).

https://bim.ie/wpcontent/uploads/2021/02/BIM,Aquaculture,Explained,Issue,26,Cultivating,Laminaria,digitata.pdf

FAO (2004). Cultured Aquatic Species Information Programme. *Laminaria japonica*. Rome: Food and Agriculture Organization of the United Nations.

Fredersdorf, J., Müller, R., Becker, S. *et al*. (2009). Interactive effects of radiation, temperature and salinity on different life history stages of the Arctic kelp *Alaria esculenta* (Phaeophyceae). Oecologia 160, 483–492. https://doi.org/10.1007/s00442-009-1326-9

Ghaderiardakani, F., Califano, G., Mohr, J.F., Abreu, M.H., Coates, J.C., Wichard, T. (2019) Analysis of algal growth- and morphogenesis-promoting factors in an integrated multi-trophic aquaculture system for farming *Ulva* spp.. Aquaculture Environment Interactions 11, 375-391. https://doi.org/10.3354/aei00319

Green, L.A., Neefus, C.D. (2016). Effects of temperature, light level, and photoperiod on the physiology of *Porphyra umbilicalis* Kützing from the Northwest Atlantic, a candidate for aquaculture. Journal of Applied Phycology 28, 1815–1826. https://doi.org/10.1007/s10811-015-0702-6

Grote, B. (2017). Recent developments in aquaculture of *Palmaria palmata* (Linnaeus) (Weber & Mohr 1805): cultivation and uses. Reviews in Aquaculture 11(1), 25-41, https://doi.org/10.1111/raq.12224

Hanelt, D., Figueroa, F.L. (2012). Physiological and photomorphogenic effects of light on marine macrophytes. In Seaweed Biology. Novel insight into ecophysiology, ecology and utilization. Wiencke and Bischof Editors, Ecological Studies 219, pp. 510.

Harrison, P.J., Hurd, C.L. (2001). Nutrient physiology of seaweeds: Application of concepts to aquaculture. Cahiers de Biologie Marine 42, 71-82.

Huntington, T., Cappell, R. (2020). English aquaculture strategy. Final Report. Produced by Poseidon Aquatic Resources Management Ltd for the Seafish Industry Authority, p 88.

Karsten, U., Dummermuth, A., Hoyer, K. *et al*. (2003). Interactive effects of ultraviolet radiation and salinity on the ecophysiology of two Arctic red algae from shallow waters. Polar Biology 26, 249–258. https://doi.org/10.1007/s00300-002-0462-z

Kerrison, P.D., Stanley, M.S., Edwards, M.D., Black, K.D. and Hughes, A.D. (2015). The cultivation of European kelp for bioenergy: site and species selection. Biomass and Bioenergy 80, 229-242. https://doi.org/10.1016/j.biombioe.2015.04.035

Kerrison, P.D., Stanley, M.S., Hughes, A.D. (2018). Textile substrate seeding of *Saccharina latissima* sporophytes using a binder: an effective method for the aquaculture of kelp. Algal Research 33, 352-357. https://doi.org/10.1016/j.algal.2018.06.005

Kerrison, P.D., Twigg, G., Stanley, M., De Smet, D., Buyle, G., Martinez Pina, A., Hughes, A.D. (2019). Twine selection is essential for successful hatchery cultivation of *Saccharina latissima*, seeded with either meiospores or juvenile sporophytes. Journal of Applied Phycology 31, 3051–3060. doi.org/10.1007/s10811-019-01793-x.

Knoop, J., Griffin, J.N., Barrento, S. (2020). Cultivation of early life history stages of *Porphyra dioica* from the British Isles. Journal of Applied Phycology 32, 459–471. https://doi.org/10.1007/s10811-019-01930-6

Lavik, A.Q. (2016). Developing a laboratory cultivation protocol for local species of *Porphyra* spp. MSc in Biology, Norwegian University of Science and Technology, pp.64.

Lobban, C.S., Harrison, P.J. (1997). Seaweed ecology and physiology. Cambridge University Press, Cambridge, pp. 366.

Lüning, K. (1984). Temperature tolerance and biogeography of seaweeds: the marine algal flora of Helgoland (North Sea) as an example. Helgolander Meeresuntersuchungen 38, 305-317.

Meichssner, R., Krost, P., Schulz, R. (2021). Experimental testing and density- and season-dependent growth in vegetative *Fucus* aquaculture and modelling of growth over one year for different cultivation scenarios. Journal of Applied Phycology 33, 3939-3950. https://doi.org/10.1007/s10811-021-02597-8

Meichssner, R., Stegmann, N., Cosin, AS. *et al.* (2020). Control of fouling in the aquaculture of *Fucus vesiculosus* and *Fucus serratus* by regular desiccation. Journal of Applied Phycology 32, 4145–4158. https://doi.org/10.1007/s10811-020-02274-2

MMO (2019). Identification of Areas of Aquaculture Potential in English Waters, MMO Project No: 1184, May 2019, pp. 109.

Mooney-McAuley, K.M., Edwards, M.D., Champenois, J., Gorman, E. (2016). Best Practice Guidelines for Seaweed Cultivation and Analysis, Public Output report of the EnAlgae project, Swansea, June 2016, pp. 36

Moreira, A., Cruz, S., Marques, R., Cartaxana, P. (2022). The underexplored potential of green macroalgae in aquaculture. Reviews in Aquaculture 14, 5–26. https://doi.org/10.1111/raq.12580

Morgan, K.C., Shacklock, P.F., Simpson, F.J. (1980). Some aspects of the culture of *Palmaria palmata* in greenhouse tanks. Botanica Marina, 23, 765–770.

Morgan, K.C., Simpson, F.J. (1981). The Cultivation of *Palmaria palmata*. Effect of Light Intensity and Nitrate Supply on Growth and Chemical Composition. Botanica Marina, 24, 273-277. http://dx.doi.org/10.1515/botm.1981.24.5.273

Munda, I.M., Lüning, K. (1977). Growth performance of Alaria esculenta off Helgoland. Helgolander wiss. Meeresunters 29, 311-314.

Northern Light Consulting (2021). Aberdeenshire Council Seaweed Cultivation – A new opportunity for Aberdeenshire. http://publications.aberdeenshire.gov.uk/dataset/0964f372-1a23-447a-bf2c-828da1ed78a1/resource/fe54ef76-d2f4-467c-912f-c2ad9e82e74e/download/aberdeenshire-council---cids-seaweed-cultivation-feasibility-study-july-2021-13092021.pdf

Redmond, S., Green, L., Yarish, C., Kim, J., Neefus C. (2014). New England Seaweed Culture Handbook-Nursery Systems. Connecticut Sea Grant CTSG-14-01. 92 pp. PDF file. https://digitalcommons.lib.uconn.edu/seagrant_weedcult/1/. 92 pp

Roesijadi, G. *et al*. (2011). Macroalgae analysis. A national GIS-based analysis of macroalgae production potential. Summary report and project plan. Prepared for the U.S. Department of Energy under contract DE-AC05-76RL01830, pp. 56.

Rolin, C., Inkster, R., Laing, J., Hedges, J., McEvoy, L. (2016). Seaweed cultivation manual. Shetland Seaweed Growers Project 2014-2016. NAFC Marine Centre, University of the Highlands and Islands, pp. 38.

Schmedes, P.S., Nielsen, M.M. (2020a). New hatchery methods for efficient spore use and seedling production of *Palmaria palmata* (dulse). Journal of Applied Phycology 32, 2183–2193. https://doi.org/10.1007/s10811-019-01998-0

Schmedes, P.S., Nielsen, M.M. (2020b). Productivity and growth rate in *Palmaria palmata* affected by salinity, irradiance, and nutrient availability—the use of nutrient pulses and interventional cultivation. Journal of Applied Phycology 32, 4099–4111. https://doi.org/10.1007/s10811-020-02248-4

Silva, P., Pereira, L. (2020). Concise review of *Osmundea pinnatifida* (Hudson) Stackhouse. Journal of Applied Phycology 32, 2761–2771. https://doi.org/10.1007/s10811-020-02183-4

Sjøtun K., Fredriksen S. (1995). Growth allocation in *Laminaria hyperborea* (Laminariales, Phaeophyceae) in relation to age and wave exposure. Marine Ecology Progress Series 126, 213-222.

Smale, D.A., Pessarrodona, A., King, N. *et al.* (2020). Environmental factors influencing primary productivity of the forest-forming kelp *Laminaria hyperborea* in the northeast Atlantic. Scientific Reports 10, 12161. https://doi.org/10.1038/s41598-020-69238-x

Smale, D.A., Wernberg, T., Yunnie, A.L.E., Vance, T. (2015). The rise of *Laminaria ochroleuca* in the Western English Channel (UK) and preliminary comparisons with its competitor and assemblage dominant *Laminaria hyperborea*. Marine Ecology 36: 1033–1044. https://doi.org/10.1111/maec.12199

Steinhagen, S., Enge, S., Cervin, G., *et al*. (2022). Harvest Time Can Affect the Optimal Yield and Quality of Sea Lettuce (*Ulva fenestrata*) in a Sustainable Sea-Based Cultivation. Frontiers in Marine Science 9:816890. doi:10.3389/fmars.2022.816890

Steinhagen, S., Enge, S., Larsson, K. *et al*. (2021). Sustainable Large-Scale Aquaculture of the Northern Hemisphere Sea Lettuce, *Ulva fenestrata*, in an Offshore Seafarm. Journal of Marine Science and Engineering 9, 615. https://doi.org/10.3390/jmse9060615

Stelzenmüller, V., Gimpel, A., Gopnick, M., Gee, K. (2017). Aquaculture site-selection and marine spatial planning: the roles of GIS-based tools and models. In: Aquaculture perspective of multi-use sites in the open ocean. The untapped potential for marine resources in the Anthropocene. Editors Buck and Langan, pp. 404

Stévant, P., Schmedes, P.S., Le Gall, L. *et al.* (2023). Concise review of the red macroalga dulse, *Palmaria palmata* (L.) Weber & Mohr. Journal of Applied Phycology 35, 523–550. https://doi.org/10.1007/s10811-022-02899-5

Sundene, O. (1962). The implications of transplant and culture experiments on the growth and distribution of *Alaria esculenta*, Nytt Magasin for Botanik 9, 155-174.

Tullberg, R.M., Nguyen, H.P., Wang, C.M. (2022). Review of the Status and Developments in Seaweed Farming Infrastructure. Journal of Marine Science and Engineering, 10, 1447. https://doi.org/10.3390/jmse10101447

Tyler-Walters, H., 2008. *Alaria esculenta* Dabberlocks. In Tyler-Walters H. and Hiscock K. Marine Life Information Network: Biology and Sensitivity Key Information Reviews, [on-line]. Plymouth: Marine Biological Association of the United Kingdom. [cited 27-01-2024]. Available from: https://www.marlin.ac.uk/species/detail/1291

van der Molen, J., Ruardij, P., Mooney, K., *et al*. (2018). Modelling potential production of macroalgae farms in UK and Dutch coastal waters. Biogeosciences 15, 1123-1147 https://doi.org/10.5194/bg-15-1123-2018

Werner, A., Dring, M. (2011), Aquaculture explained no. 27 - cultivating *Palmaria palmata*. Bord Iascaigh Mhara, pp. 76

Zhu, L., Lei, J., Huguenard, K., Fredriksson, D.W. (2021). Wave attenuation by suspended canopies with cultivated kelp (*Saccharina latissima*). Coastal Engineering, 168, p.103947. https://doi.org/10.1016/j.coastaleng.2021.103947

World Class Science for the Marine and Freshwater Environment

We are the government's marine and freshwater science experts. We help keep our seas, oceans and rivers healthy and productive and our seafood safe and sustainable by providing data and advice to the UK Government and our overseas partners. We are passionate about what we do because our work helps tackle the serious global problems of climate change, marine litter, over-fishing and pollution in support of the UK's commitments to a better future (for example the UN Sustainable Development Goals and Defra's 25 year Environment Plan).

We work in partnership with our colleagues in Defra and across UK government, and with international governments, business, maritime and fishing industry, non-governmental organisations, research institutes, universities, civil society and schools to collate and share knowledge. Together we can understand and value our seas to secure a sustainable blue future for us all, and help create a greater place for living.

Pakefield Road, Lowestoft, Suffolk, NR33 0HT

The Nothe, Barrack Road, Weymouth DT4 8UB

www.cefas.co.uk | +44 (0) 1502 562244