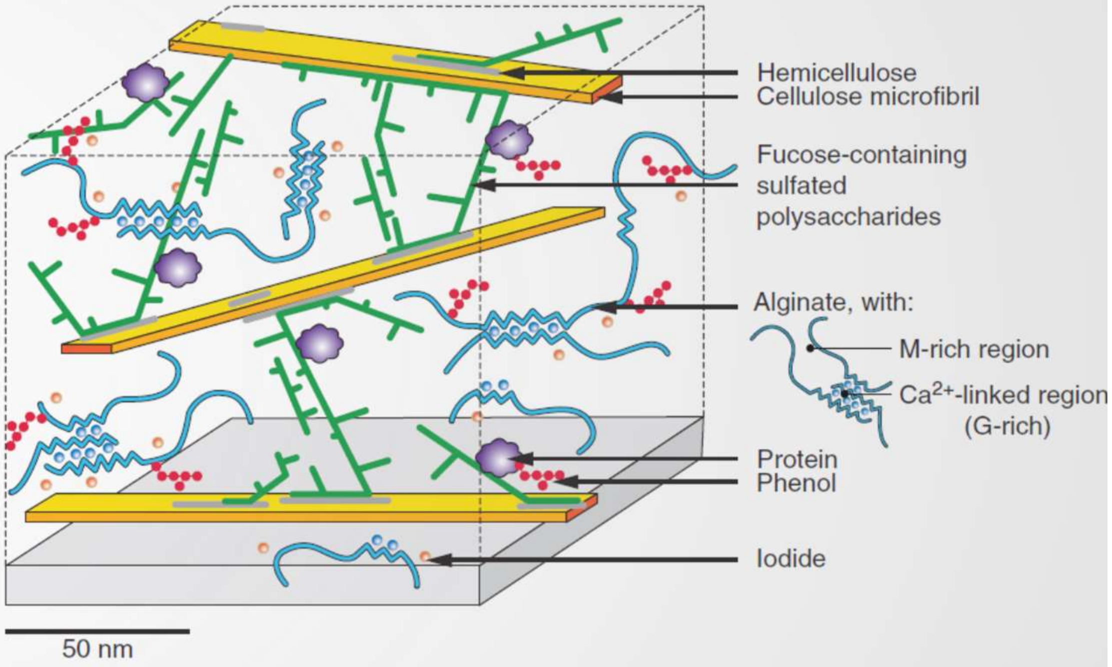
Seaweed Biorefining

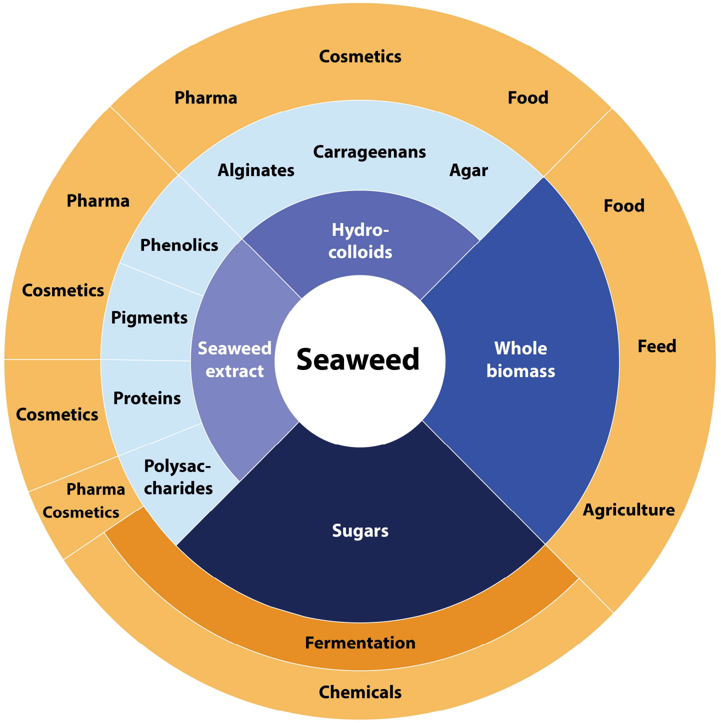
Seaweed farming can contribute to the sustainability of food, chemicals, and material production

It is carbon negative, doesn't compete for land and doesn't require fresh water, fertilizer or pesticides

Annual world production 26.1 million tons (mostly in Asia) ~7.5 USD billion
Production in Europe 250 000 tons Market value €70/ ton +

Seaweed cell walls contain valuable pigments, polysaccharides and other chemicals





Products

Feed
Bulk feed
Feed additives

Agriculture
Fertiliser
Biostimulants

Food
Bulk food
Gelling agents
Thickeners

Pharma
Excipients
Gelling agents
Wound healing
Antibacterial
Antiviral
Anticancer

Cosmetics
Gelling agents
Photoprotectants
Antioxidants

Chemicals
Platform chemicals
Biofuels

16:00	**Session 6: Seaweed biorefining** *Chair: Leonardo Gomez, University of York*	
16:05	**Research progress and knowledge gaps in seaweed cultivation and valorisation** *Thierry Tonon, University of York*	**17**
16:25	**Seaweed production in the UK: status, challenges and developments in aquaculture** *Elisa Capuzzo, Cefas*	**18**
16:45	**Flash presentation: Sustainable seaweed: analysing environmental impacts of production and use** *Tom McMurray, Queens University Belfast*	**P15**
16:50	**Sustainable packaging in the context of a seaweed biorefinery focused on biopolymeric materials** *Erinc Bahcegul, Notpla Ltd.*	**19**
17:10	**The Norwegian Seaweed Biorefinery Platform** *Finn Lillelund Aachmann, NTNU Norwegian University of Science and Technology*	**20**

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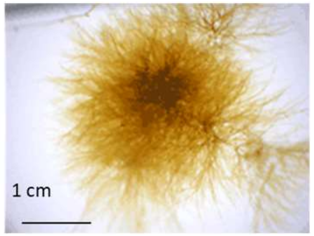
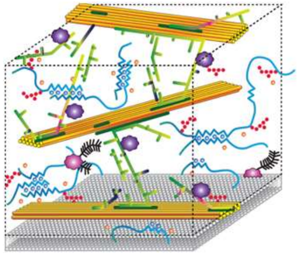
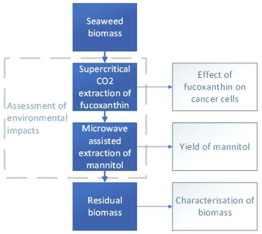
Research progress and knowledge gaps in seaweed cultivation and valorisation

Dr Thierry Tonon

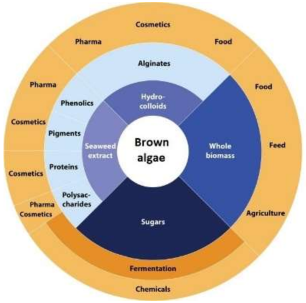
Centre for Novel Agricultural products (CNAP)
Department of Biology - University of York (UK)







Seaweed biomass
Supercritical CO2 extraction of fucoxanthin
Microwave assisted extraction of mannitol
Residual biomass
Assessment of environmental impacts
Effect of fucoxanthin on cancer cells
Yield of mannitol
Characterisation of biomass



BB Net
Biomass
Biorefinery
Network

3rd BBNet Conference: Biorefining – Clean Growth – Net Zero

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Seaweeds… weeds or not weeds?


Palmaria palmata


Eucheuma cottoni


Kappaphycus alvarezzi


Porphyra yezoensis

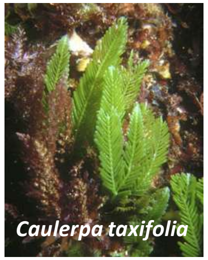

Gelidium sp.


Gracilaria sp.


Chondrus crispus


Asparagopsis spp.


Enteromorpha intestinalis

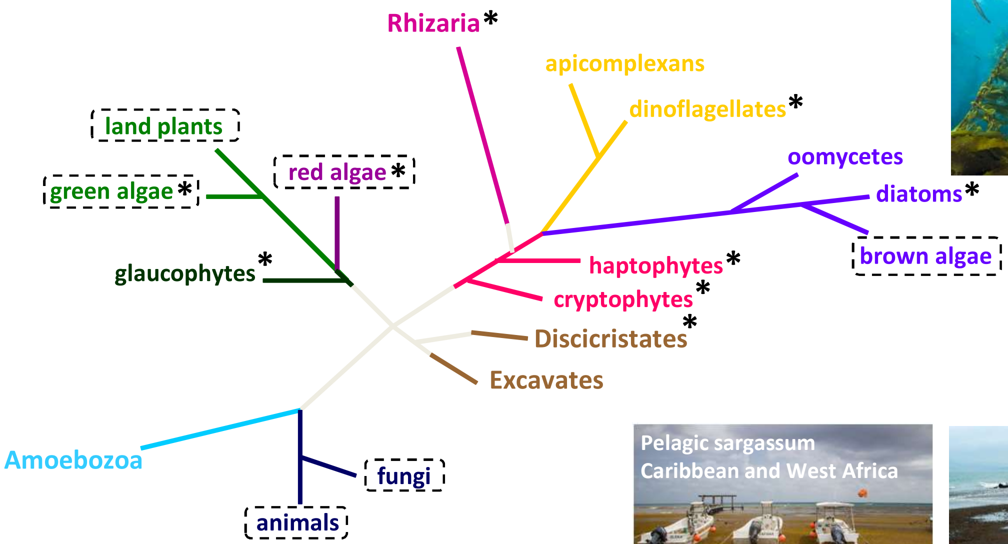

Caulerpa taxifolia


Ulva spp.


Poole (UK)

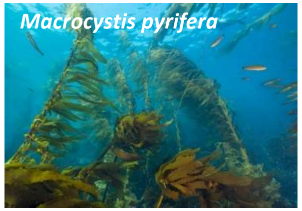

Brittany (France)


China


Rhizaria*
apicomplexans
dinoflagellates*
oomycetes
diatoms*
brown algae
haptophytes*
cryptophytes*
Discicristates*
Excavates
land plants
red algae*
green algae*
glaucophytes*
Amoebozoa
fungi
animals

Complex multicellularity
* Group containing algae

Adapted from Baldauf J. Syst. Evol. 2008


Macrocystis pyrifera


Fucus vesiculosus


Saccharina latissima


Laminaria digitata


Pelagic sargassum
Caribbean and West Africa


Rugulopteryx okamurae
Europe and
Africa Mediterranean coastline


Alaria esculenta

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Some seaweeds related facts…

- Global seaweed market: $6.5 B in 2021 ⇨ $14.6 B by 2031 *(Allied Market Research 2023)*

Long line of *Saccharina japonica* (China)

- FAO 2021:

- Seaweed production ~ 35 million tonnes - 97 % from Asia

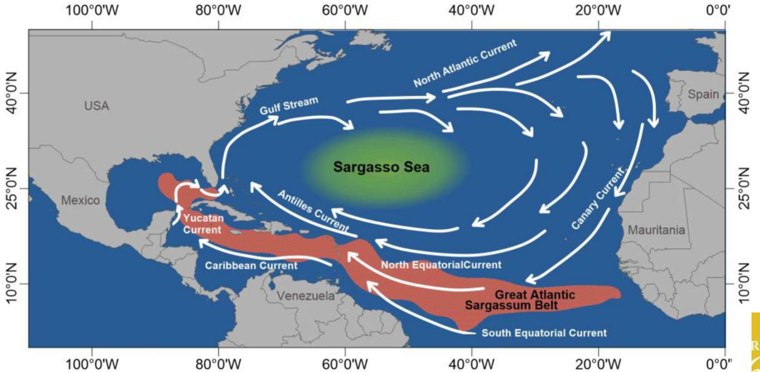
- 97 % from farming and 3 % from wild harvesting

- 99 % of farming from Asia - China, Indonesia, South Korea, the Philippines, North Korea, Japan

- Seaweeds produced: 51.5 % red, 47.5 % brown, 1% green

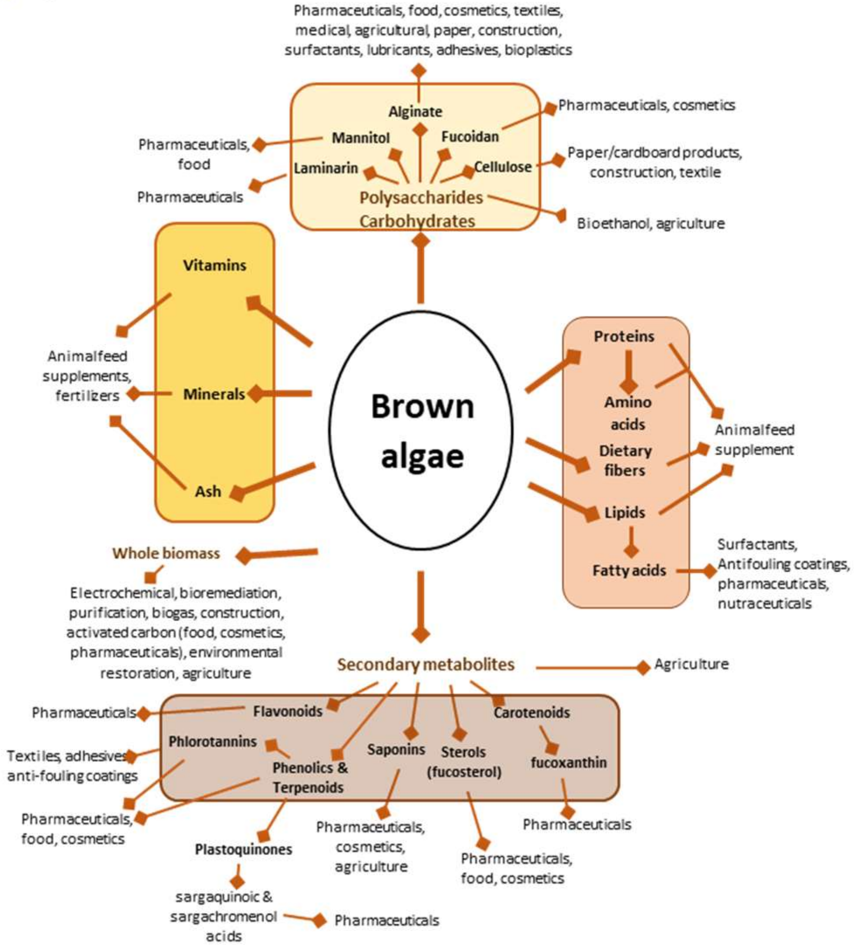
- Most seaweeds produced (95%): Laminaria/Saccharina, Kappaphycus/Euchema, Gracilaria, Porphyra/Pyropia, Undaria

- These numbers do not consider invasive/bloom forming seaweeds
E.g. 22 million tons of floating pelagic sargassum in 2022

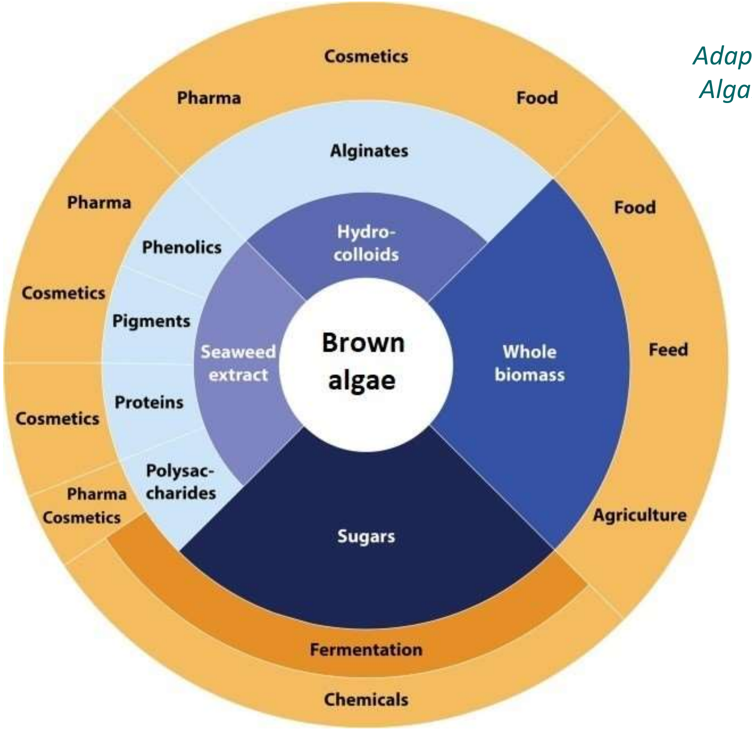


Miranda et al. Front. Mar. Sci. 2021

Brown algae: from composition to applications



Adapted from Desrochers et al.
FAO Fisheries and Aquaculture Technical Paper No. 686 (2022)



Adapted from Bennett et al.
Algal. Res 2023

Examples of market values ($ M)		
	2023	2030
Alginates	580	780
Fucoidans	47	203
Fucoxanthin	209	295

Several sources

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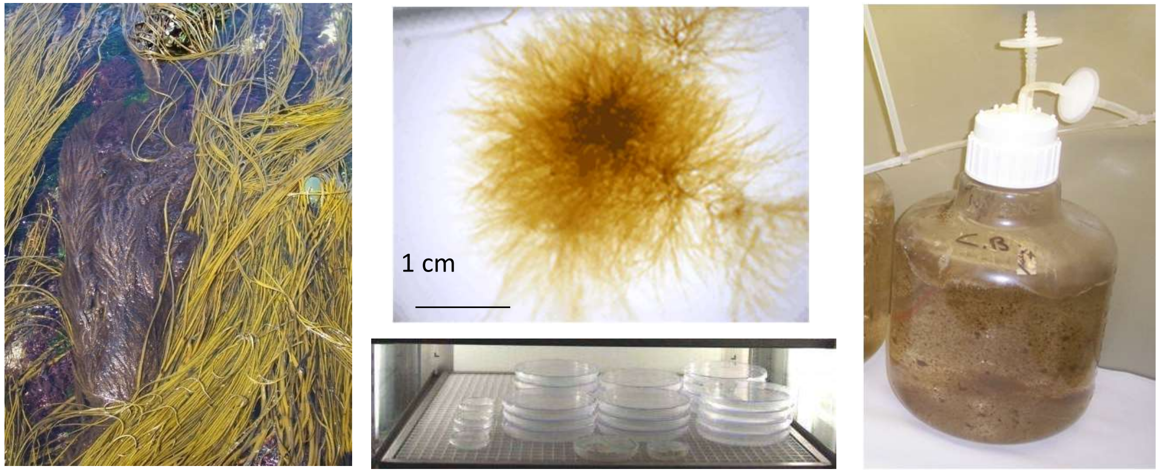
Brown algae: the MODEL and the CROP

- **The MODEL: *Ectocarpus* sp. 7**



- Cosmopolitan distribution

- Small size of the organism

- Small size of its nuclear genome (214 Mb)

- Short time life cycle completed in the lab (~3 months)

- **The CROP: *Saccharina latissima***

- Found across the North Atlantic, Estearn Pacific, and Arctic Oceans

- The most farmed kelp species in Europe and North America

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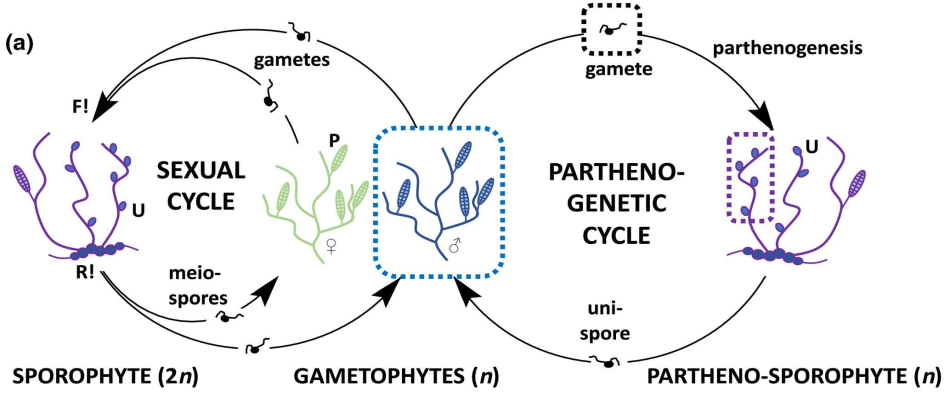
The model *Ectocarpus* sp. 7

Adapted from Cock et al. J. Phycol. 2023

2023	Comparative genomics	Phaeoexplorer brown algal genome resource
2022	Transcriptomics	Shiny transcriptomic aggregator
2021	Reverse genetics	CRISPR-Cas9-based gene knockouts ←
	Epigenetics	ChIP-seq analysis of histone modifications
2020	Genome assembly	Hi-C-based chromosome-level assembly
2017	Reverse genetics	RNA interference using small interfering RNAs ←
	Forward genetics	Positional cloning and cloning-by-sequencing
	Quantitative genetics	Identification of quantitative trait loci
	Genetic map	High density RAD-seq-based genetic map
	Taxonomy	Improved delimitation of *Ectocarpus* species
	Non-coding RNAs	Catalogue of lncRNAs
2015	Non-coding RNAs	Identification of microRNAs
2014	EctoGEM	*Ectocarpus* genome-scale metabolic network
2010	Genome sequence	Complete, annotated genome sequence ←
	Genetic map	Microsatellite-based genetic map
	Proteomics	Proteomic analysis of stress response
2009	Transcriptomics	Microarray-based transcriptome analysis
2008	Subcellular targeting	Hectar prediction of subcellular location
2004	Model system	*Ectocarpus* proposed as a genetic and genomic model
1997	Classical genetics	Segregation analysis of genetic variants
1964	Life history	Completion of life cycle in the laboratory ←



Badis et al. New Phytol. 2021


New Phytologist

The Ectocarpus genome sequence

⇨ To explore the functions of brown algal genes in a broad range of contexts including cell biology, development, metabolism, reproduction, interactions with other organisms, and resistance to stress.

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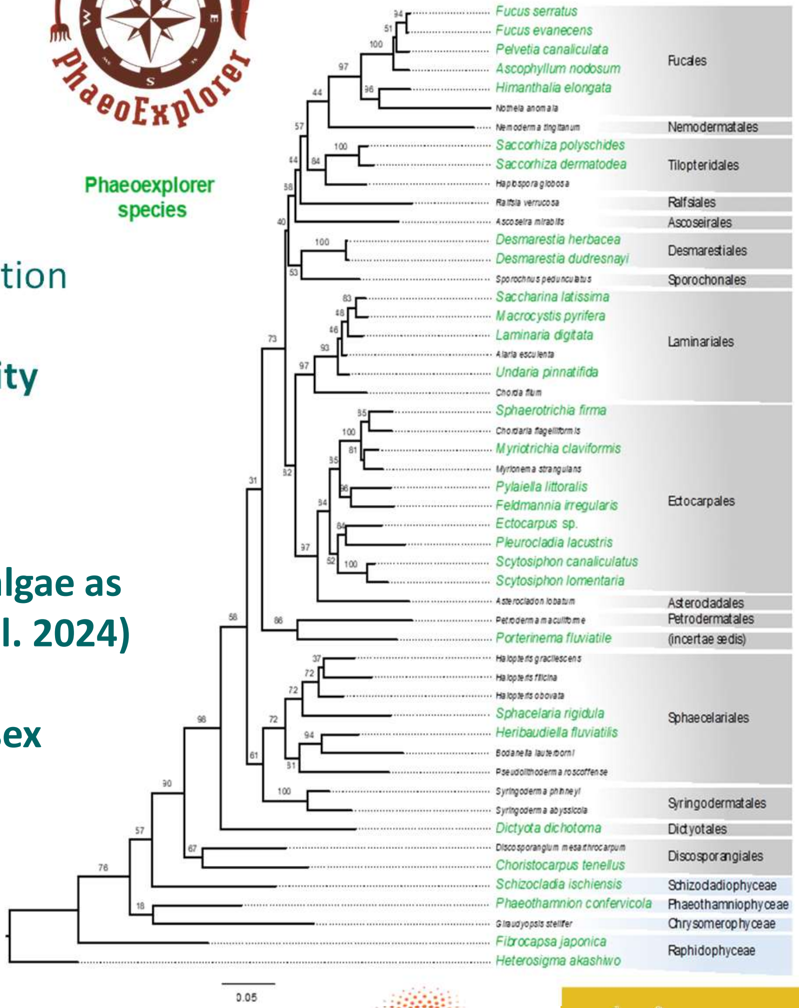
The Phaeoexplorer project

- Genome and transcriptome data for **40 brown algae** and **4 sister species**

- To establish **a genomic data resource** designed specifically to facilitate investigation of the **emergence and diversification of key biological traits within the brown algae**, particularly those associated with the transition to **complex multicellularity**

Phaeoexplorer species



bioRxiv beta
THE PREPRINT SERVER FOR BIOLOGY

- Evolutionary genomics of the emergence of brown algae as key components of coastal ecosystems (Denoeud et al. 2024)

- Origin and evolutionary trajectories of brown algal sex chromosomes (Barrera-Redondo et al. 2024)

FRANCE GÉNOMIQUE
AGENCE NATIONALE DE LA RECHERCHE ANR
GENOSCOPE
CNRS
CNRS UPMC Station Biologique Roscoff
IDEALG seaweed for the future
GENIALG
erc Sexsea
UNIVERSITY of York RESEARCH

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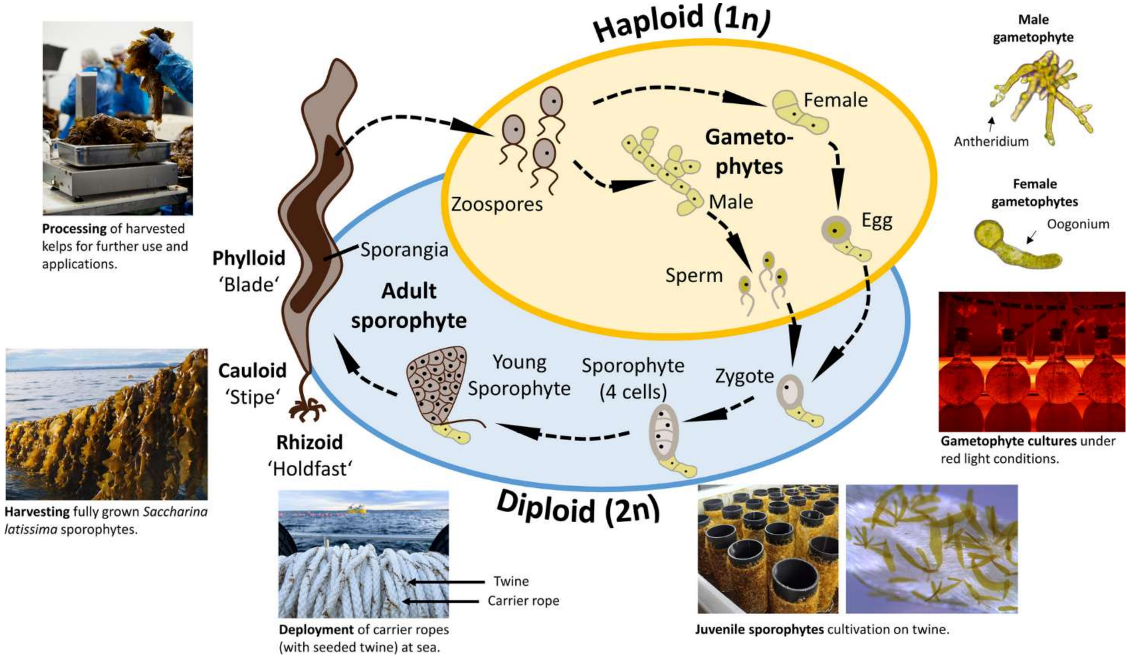
The crop *Saccharina latissima*

- **Cultivation process: nursery stage + sea farming stage**

- **Full life cycle controlled in the laboratory**

⇨ **Seed banking and hatcheries**



Processing of harvested kelps for further use and applications.

Harvesting fully grown *Saccharina latissima* sporophytes.

Gametophyte cultures under red light conditions.

Deployment of carrier ropes (with seeded twine) at sea.

Juvenile sporophytes cultivation on twine.

Sather et al. J. Appl. Phycol. 2024

- **Recent advances on the roles of abiotic factors on the biology and development of the gametophytes**

- **Better understanding of the influence of nursery practices on biomass yield and composition after sporophytes sea farming**

- **More evidences on the impact of site location, deployment time and depth the on growth, quality and chemical composition of the biomass**

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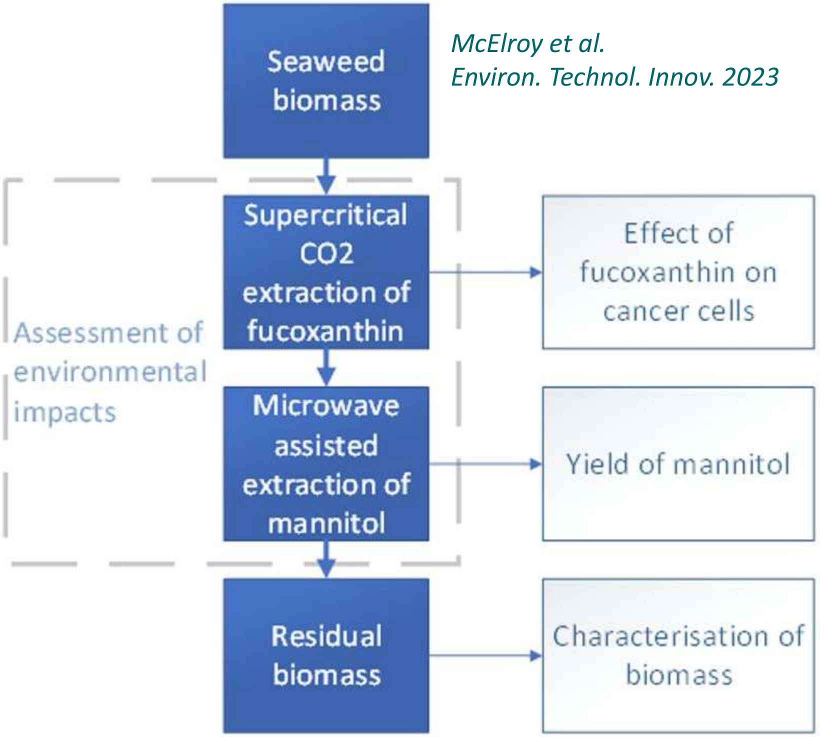
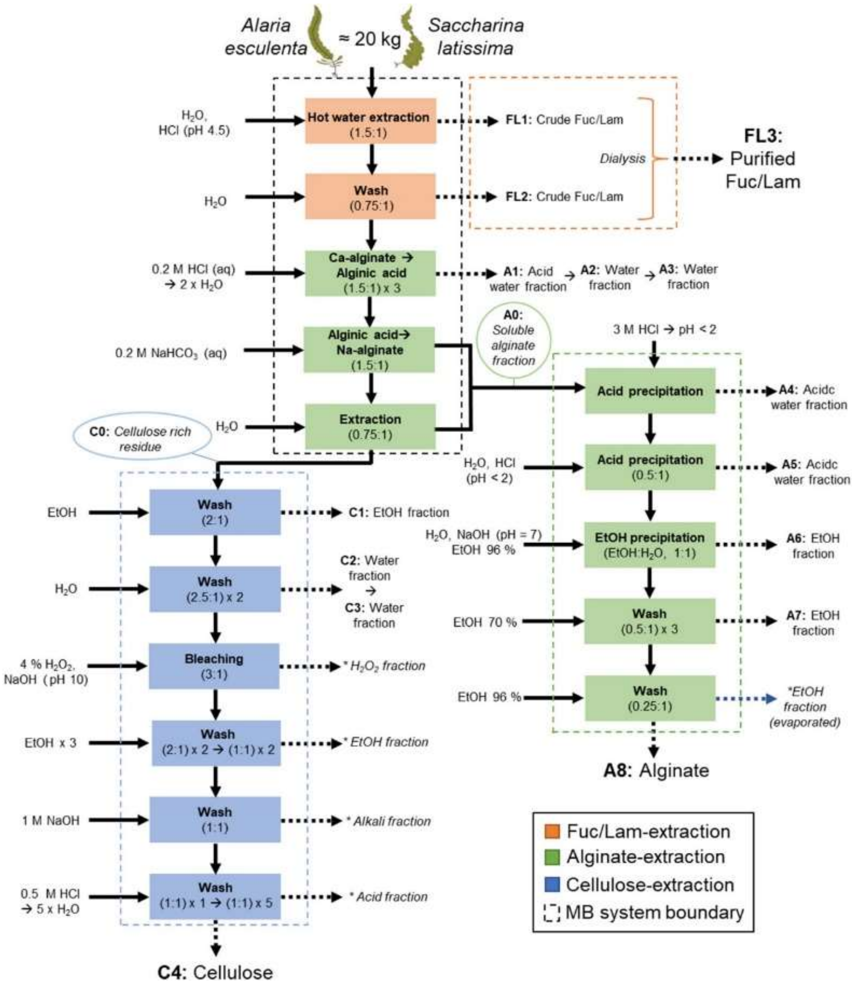
The crop *Saccharina latissima*

- **Different biorefinery processes for several targeted products**


Seaweed biomass
Supercritical CO2 extraction of fucoxanthin
Microwave assisted extraction of mannitol
Residual biomass
Assessment of environmental impacts
Effect of fucoxanthin on cancer cells
Yield of mannitol
Characterisation of biomass

McElroy et al.
Environ. Technol. Innov. 2023

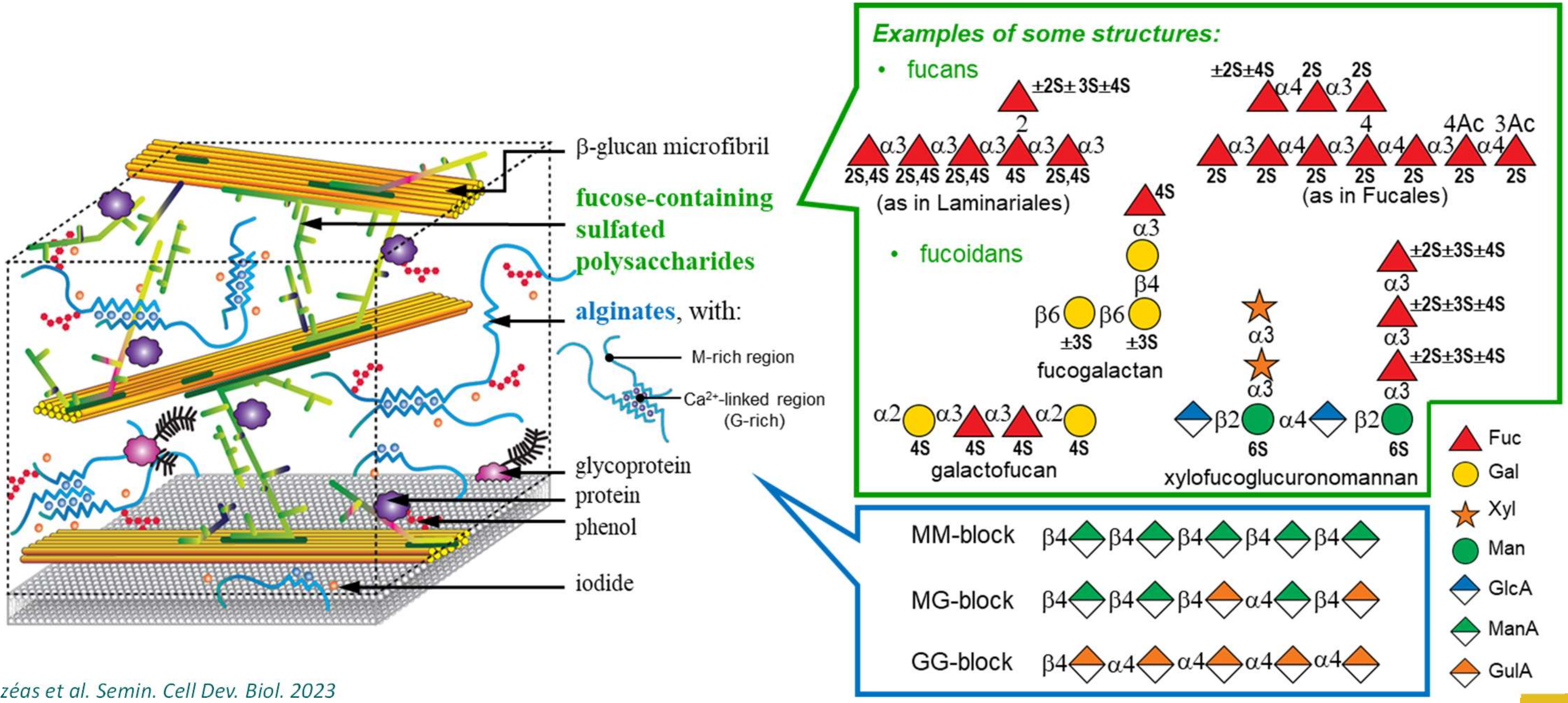
Birgersson et al.
Algal Res. 2023



- Optimisation of $ScCO_2$ extraction of fucoxanthin
- Extraction of fucoidans and alginate possible in residual biomass

- **Sequential chemical extraction of laminarin, fucoidan, alginate and cellulose**
- **Development of mild chemical methods to avoid compromising the molecular weight of polysaccharides (alginate)**

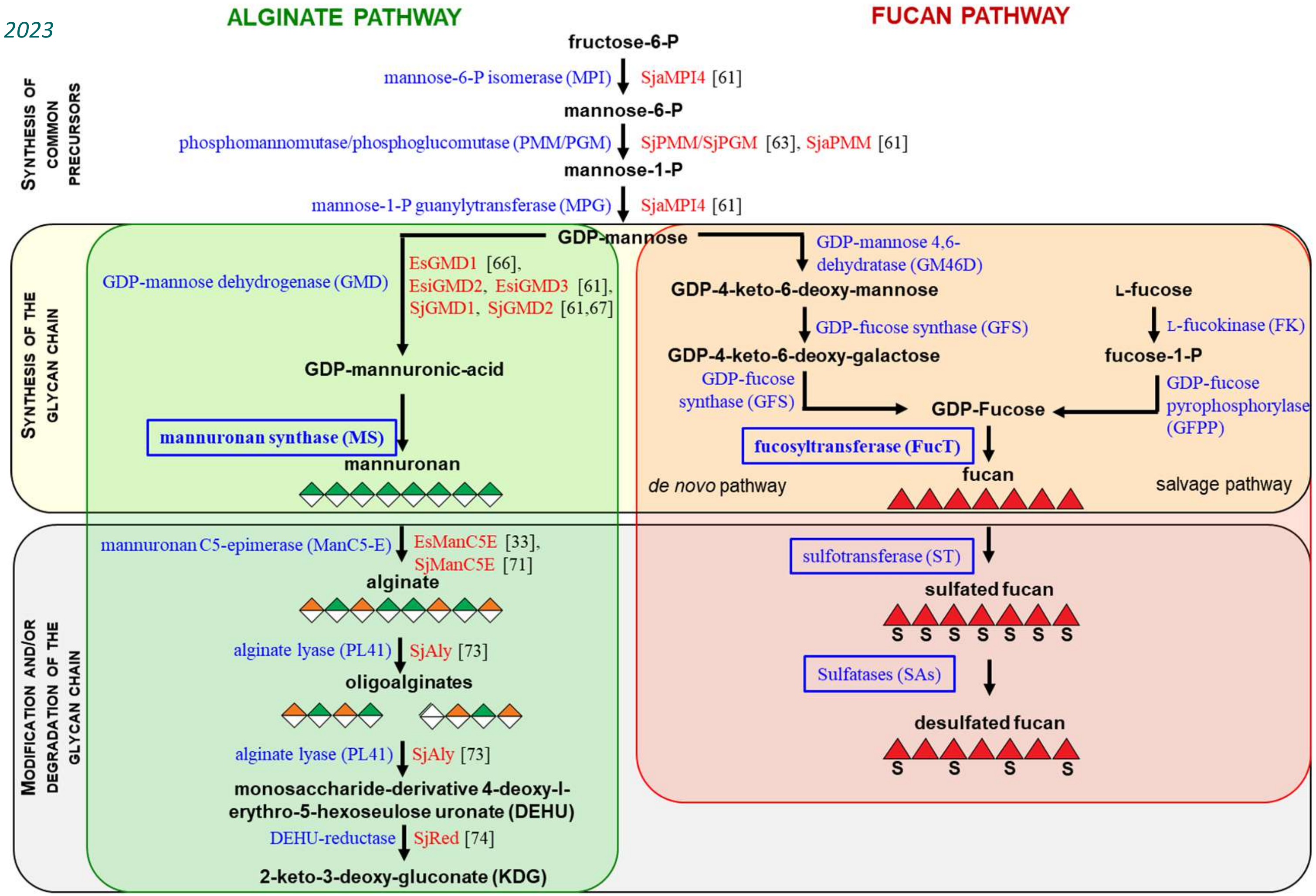
Gaps in basic knowledge on brown algae: the cell wall



Mazéas et al. Semin. Cell Dev. Biol. 2023

Gaps in basic knowledge on brown algae: the cell wall

Mazéas et al. Semin. Cell Dev. Biol. 2023



ALGINATE PATHWAY

FUCAN PATHWAY

SYNTHESIS OF COMMON PRECURSORS

fructose-6-P

mannose-6-P isomerase (MPI) SjaMPI4 [61]

mannose-6-P

phosphomannomutase/phosphoglucomutase (PMM/PGM) SjPMM/SjPGM [63], SjaPMM [61]

mannose-1-P

mannose-1-P guanylytransferase (MPG) SjaMPI4 [61]

SYNTHESIS OF THE GLYCAN CHAIN

GDP-mannose

GDP-mannose dehydrogenase (GMD) EsGMD1 [66], EsiGMD2, EsiGMD3 [61], SjGMD1, SjGMD2 [61,67]

GDP-mannuronic-acid

mannuronan synthase (MS)

mannuronan

GDP-mannose 4,6-dehydratase (GM46D)

GDP-4-keto-6-deoxy-mannose

GDP-fucose synthase (GFS)

GDP-4-keto-6-deoxy-galactose

GDP-fucose synthase (GFS)

GDP-Fucose

L-fucose

L-fucokinase (FK)

fucose-1-P

GDP-fucose pyrophosphorylase (GFPP)

fucosyltransferase (FucT)

fucan

de novo pathway

salvage pathway

MODIFICATION AND/OR DEGRADATION OF THE GLYCAN CHAIN

mannuronan C5-epimerase (ManC5-E) EsManC5E [33], SjManC5E [71]

alginate

alginate lyase (PL41) SjAly [73]

oligoalginates

alginate lyase (PL41) SjAly [73]

monosaccharide-derivative 4-deoxy-l-erythro-5-hexoseulose uronate (DEHU)

DEHU-reductase SjRed [74]

2-keto-3-deoxy-gluconate (KDG)

sulfotransferase (ST)

sulfated fucan

S S S S S S S

Sulfatases (SAs)

desulfated fucan

S S S S

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Potential directions for seaweed research (biology-engineering)…

- **Biological knowledge**: adapt and/or develop new analytical tools, create new resources

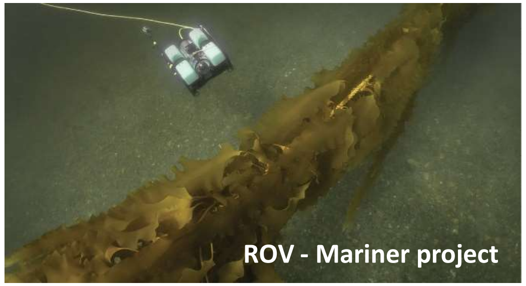
Rotten hole disease
Saccharina latissima

- **Selection (and breeding?)** to develop climate-resilient and productive strains – need to limit impact on local genetic diversity:

- Abiotic factors: habitat degradation (water pollution, rising sea temperatures, ocean acidification)

- Biotic factors : diseases – biosecurity; epiphytism – biofouling

- **Seed banks and hatcheries**: more species, more locations to make the industry more resilient



ROV - Mariner project

- **Cultivation methods**: from “low tech” to “high tech”?

- On-shore, shallow water, intertidal zone, off-shore

- New equipment and farming techniques to be more cost-effective, e.g. ROVs for farm inspection and biomass quantification and composition

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Potential directions for seaweed research (biology-engineering)…

- **Local knowledge on feedstock**: productivity, yield, seasonal variations/consistency in biomass composition

- **Environmental impact of seaweed farming** and **assessment of ecosystem service benefits** provided by seaweeds

- **Biomass processing approaches** combining physical, chemical and enzymatic treatment to find the best trade-off between costs and sustainability.

- **New products**

SEABALANCE – Emulsifier (Carbonwave)

Packaging (Notpla)

⇨ Combine biology and engineering research with innovation to develop seaweed biotechnology and support the seaweed industry as part of the Blue Economy

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Research progress and knowledge gaps in seaweed cultivation and valorisation

- Colleagues in CNAP
- Previous colleagues at the Station Biologique de Roscoff
- You for your attention

3rd BBNet Conference, 11 April 2024

Seaweed production in the UK: status, challenges and developments in aquaculture

Centre for Environment
Fisheries & Aquaculture
Science

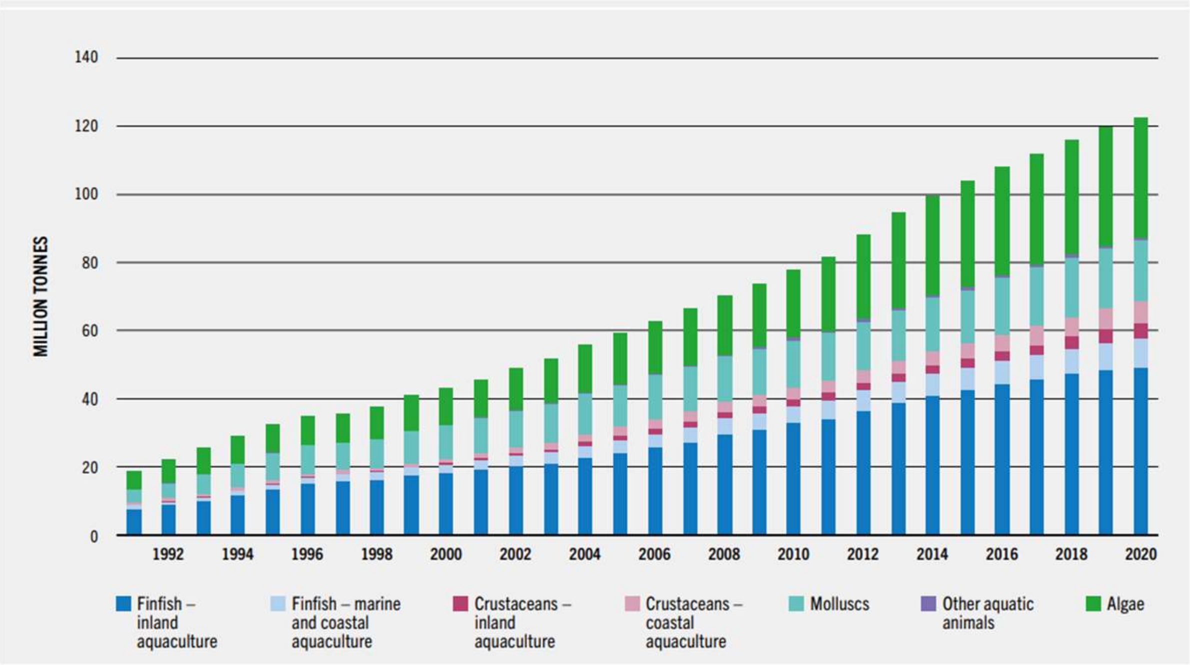
Cefas

Elisa Capuzzo | **Senior Ecosystem Scientist**

Global algae production

- 2nd largest aquaculture crop

- 35 million tonnes of algae produced in 2020
- USD 16.5 billion market value
- Asian countries responsible for majority of production



Source: FAO 2022

Centre for Environment Fisheries & Aquaculture Science

elisa.capuzzo@cefas.gov.uk
@dictioca

Cefas

UK seaweed industry

Food / feed / soil enricher

Late 17th & 18th cent.

Soda ash

(glass, soap, linen bleaching)

19th & early 20th cent.

Iodine

(tincture of iodine)

20th cent.

Hydrocolloids

(gelling agent in food and non-food applications)

Resurgence in the last decade & development of seaweed aquaculture

Drivers:

- Multiple uses and products (e.g. food, bioactives)
- Ecosystem services (bioremediation, provision of habitat)
- Alternative livelihood, job opportunities, new value chains

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UK production – wild harvest & aquaculture


https://www.bbc.co.uk/ news/

https://www.uistasco.com/scottish-seaweed-harvesting/

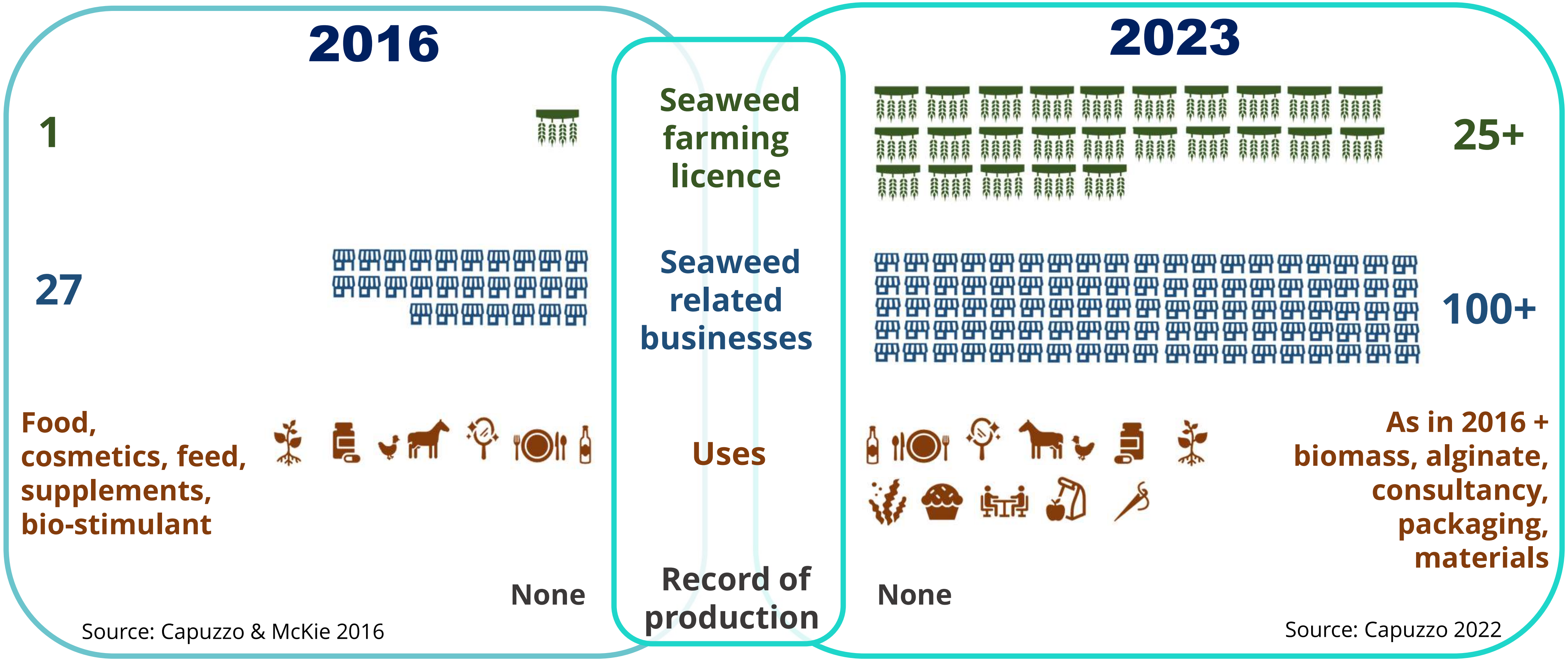

https://saeseaweed.co.uk/

- By hand (labour intensive)
- 'Limited' quantities harvested
- Variety of species

Development of seaweed aquaculture in the UK over the last decade

elisa.capuzzo@cefas.gov.uk
@dictioca

A developing industry in the UK



	2016	2023
Seaweed farming licence	1	25+
Seaweed related businesses	27	100+
Uses	Food, cosmetics, feed, supplements, bio-stimulant	As in 2016 + biomass, alginate, consultancy, packaging, materials
Record of production	None	None

Source: Capuzzo & McKie 2016

Source: Capuzzo 2022

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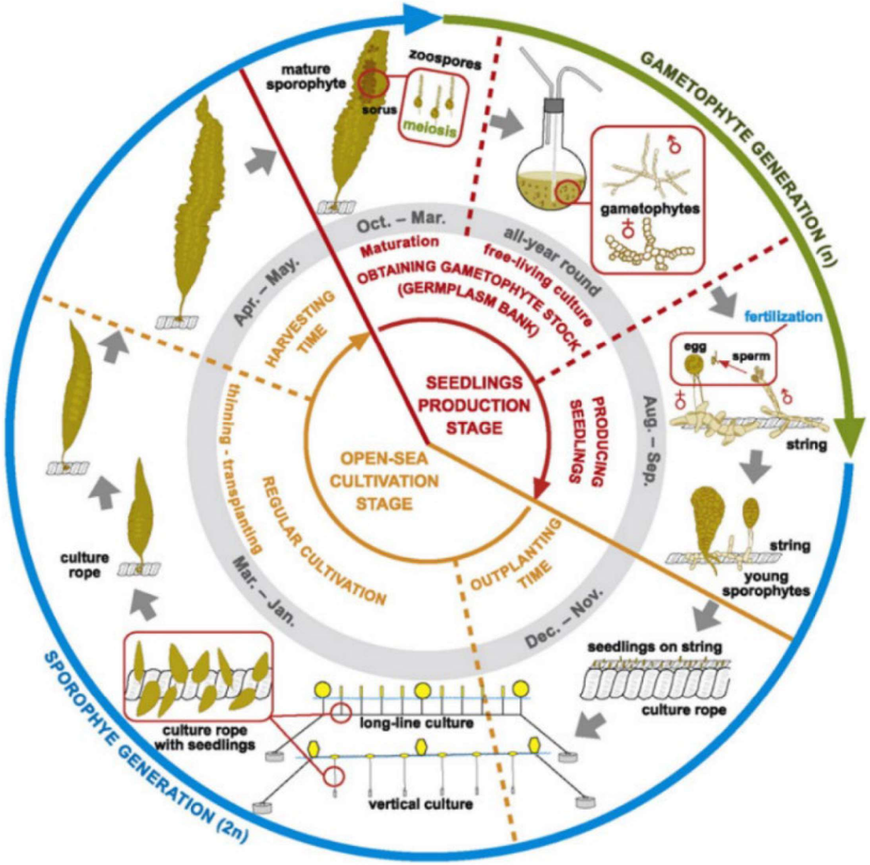
@dictioca

Cefas

Getting started with seaweed farming - challenges

- Which species? → Few species are currently successfully farmed in the UK
- Where? → Optimal location with suitable environmental conditions
- How? → Different methods available
- Which use? → Will determine production & processing

Need of a marine licence!



Tullberg et al. 2022

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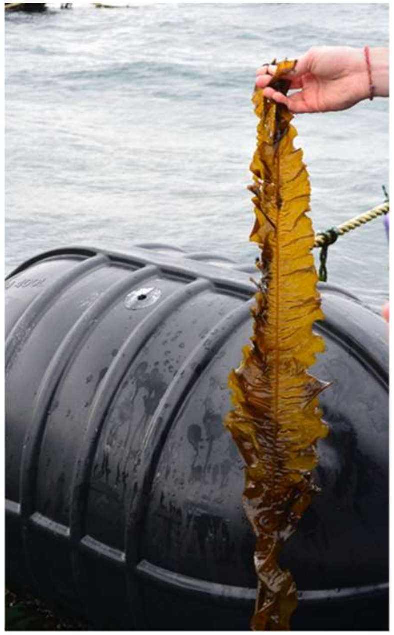
Seaweed species



***Saccharina latissima*, *Laminaria digitata*, *Laminaria hyperborea*, *Alaria esculenta*,**

***Palmaria palmata*, *Porphyra* spp [R&D] *Osmundea pinnatifida* [R&D]**

***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 yet due to uncertainty around the species' life cycle

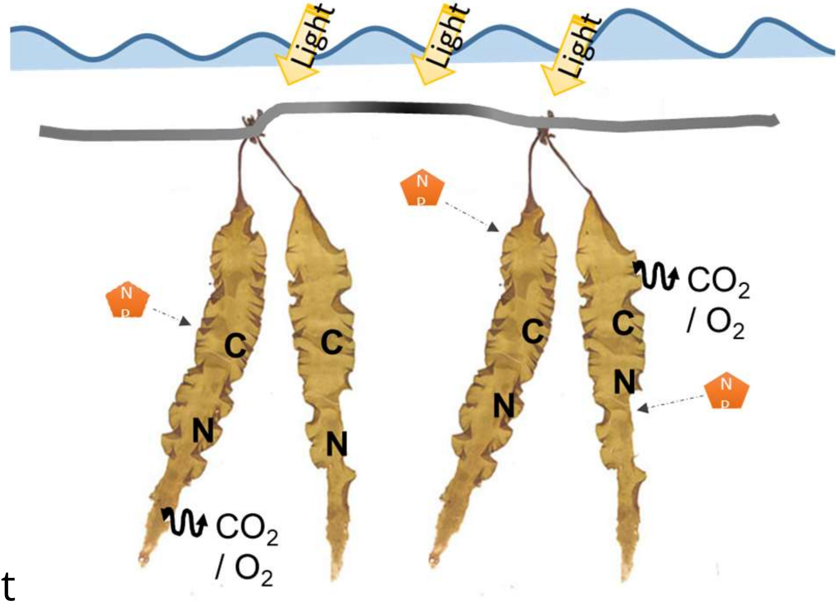
photo credit: the Cornish Seaweed Company

elisa.capuzzo@cefas.gov.uk
@dictioca

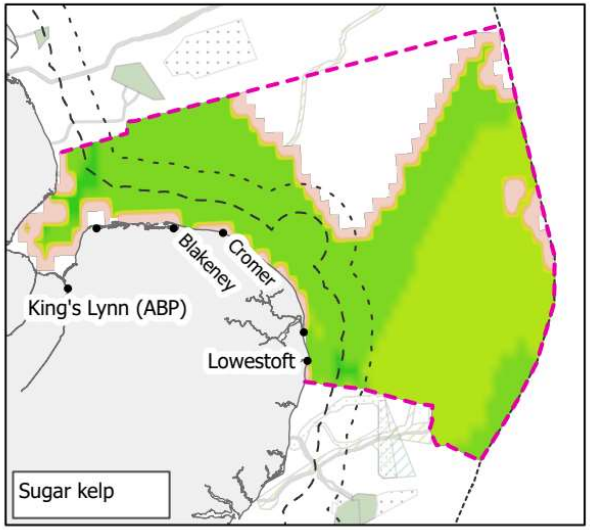
Location, location, location

- Temperature
- Salinity
- Light availability
- Nutrients
- Water movement
- Water quality
- Depth
- Distance from port

- Other uses of the area



Example of aquaculture suitability maps



https://hethelinnovation.com/seaweed-in-east-anglia/mapping-the-opportunity-for-colocation/

Production related strongly to nutrient & light: low nutrient concentrations and/or poor light give poor production.

Very high nutrient concentrations give poor carbohydrate content

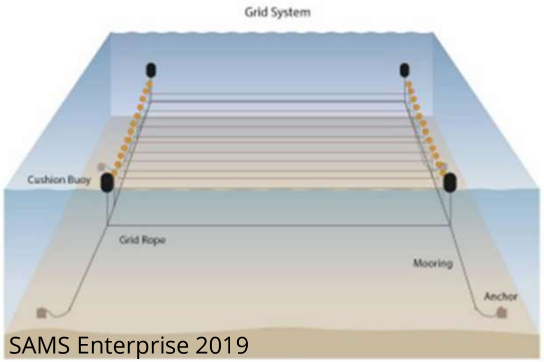
Van der Molen et al. 2018

Which method?

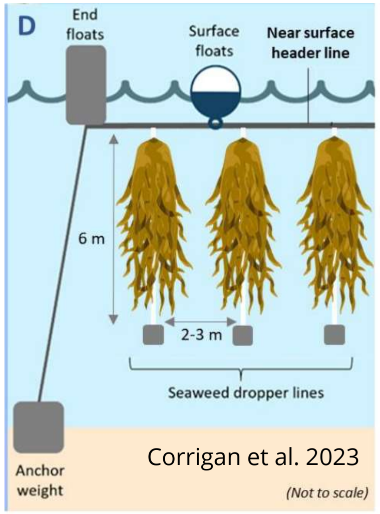
Multiple techniques (longline, droppers,...) different substrata to grow seaweed (e.g. twine, mesh).

Methods chosen to suit location, farm size, yield, species farmed, end uses and environmental conditions.

Not possible to identify “one method that fits all locations”

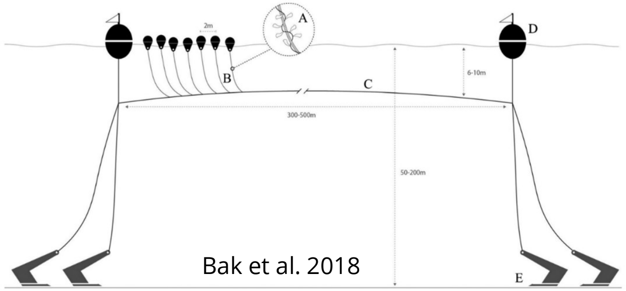


SAMS Enterprise 2019



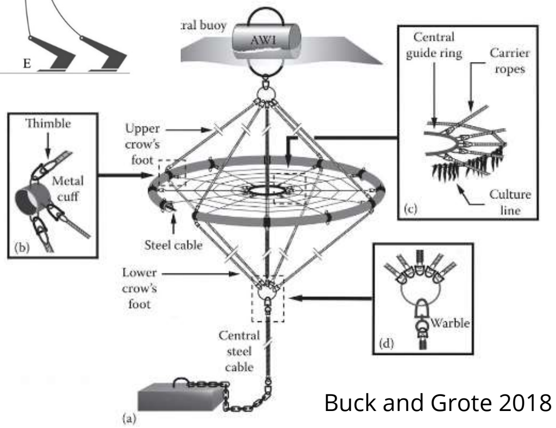
Corrigan et al. 2023

https://www.innovationintextiles.com



Bak et al. 2018

https://www.northseafarmers.org/



Buck and Grote 2018

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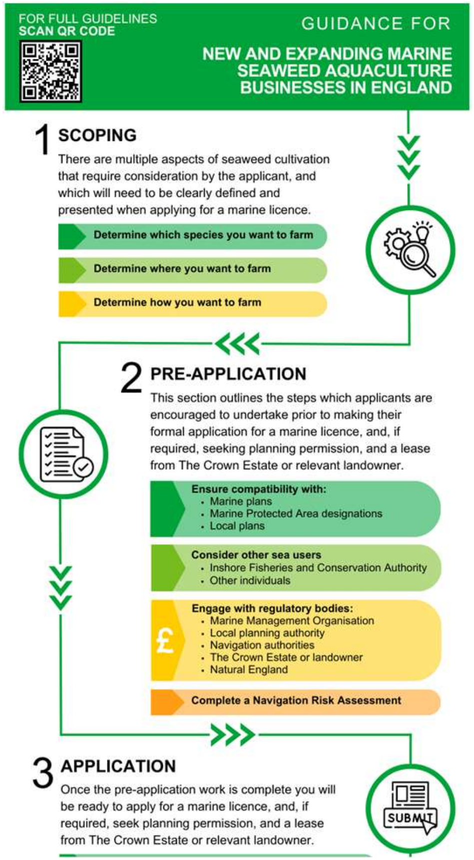
Cefas

Marine licence & social licence to operate



FOR FULL GUIDELINES
SCAN QR CODE

GUIDANCE FOR

NEW AND EXPANDING MARINE SEAWEED AQUACULTURE BUSINESSES IN ENGLAND

1 SCOPING

There are multiple aspects of seaweed cultivation that require consideration by the applicant, and which will need to be clearly defined and presented when applying for a marine licence.

- **Determine which species you want to farm**
- **Determine where you want to farm**
- **Determine how you want to farm**

2 PRE-APPLICATION

This section outlines the steps which applicants are encouraged to undertake prior to making their formal application for a marine licence, and, if required, seeking planning permission, and a lease from The Crown Estate or relevant landowner.

Ensure compatibility with:
- Marine plans
- Marine Protected Area designations
- Local plans

Consider other sea users
- Inshore Fisheries and Conservation Authority
- Other individuals

£ **Engage with regulatory bodies:**
- Marine Management Organisation
- Local planning authority
- Navigation authorities
- The Crown Estate or landowner
- Natural England

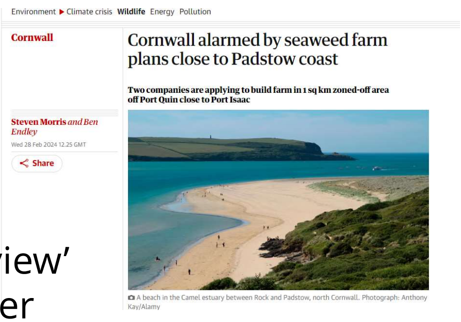
Complete a Navigation Risk Assessment

3 APPLICATION

Once the pre-application work is complete you will be ready to apply for a marine licence, and, if required, seek planning permission, and a lease from The Crown Estate or relevant landowner.

Cornwall seaweed farms opponents celebrate as plans dropped

6 January



Cornwall

Cornwall alarmed by seaweed farm plans close to Padstow coast

Two companies are applying to build farm in 1 sq km zoned-off area off Port Quin close to Port Isaac

Steven Morris *and Ben Endley*

Wed 28 Feb 2024 12.25 GMT

A beach in the Camel estuary between Rock and Padstow, north Cornwall. Photograph: Anthony Kay/Alamy

- Farm ‘ruins the view’
- Conflict with other uses (e.g. recreation)
- Uncertainty about environmental impact of seaweed aquaculture

Anger over seaweed farms off north Cornish coast

A group of campaigners from Save Port Quin walked down to the cliffs on Friday

Locals in beautiful UK seaside village outraged as huge new seaweed farm set to ruin view

The company behind the scheme withdrew their original application after a public outcry.

By ISABELLA MARSANS, OLIVIER VERGNAULT

09:09, Thu, Feb 15, 2024 | UPDATED: 10:08, Thu, Feb 15, 2024

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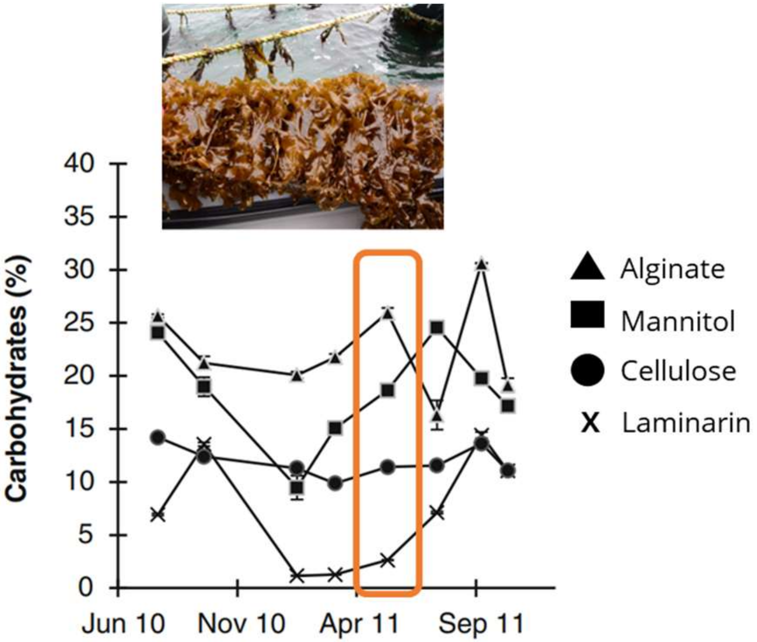
Harvesting time – April to June

Composition



Schiener et al. 2015

Biofouling

Rolin et al. 2017

Epiphytes

Tunicates

Bryozoan

Highest yield in June
Biofouling start in May → highest in August

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Post-harvest primary-processing / stabilisation

Harvested seaweed need to be stabilised quickly

Primary processing:
- drying
- lactic acid fermentation & storage under anaerobic conditions
- freezing

May potentially also need blanching, chopping, grinding

Processing may affect seaweed properties and consequently the best used for biomass

Processing can require high energy consumption

https://www.bbc.co.uk/news/business-53610683

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Conclusions

- Seaweed industry is a growing area in the UK - more farms, more businesses & more products, BUT still no records of production
- There is an increased product and business diversification
- Knowledge gaps and challenges are still present for production, processing and value chain (e.g. technical, financial, market)
- Need for innovation and R&D to amplify opportunities, drive sector development; increased knowledge sharing

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Fisheries & Aquaculture
Science

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Thanks for your attention

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Cefas

Sustainable Seaweed:

Analysing Environmental Impacts of Production & Use

Authors: Tom McMurray, Beatrice Smyth, Joe Livingstone, Pamela Walsh
Email: tmcmurray04@qub.ac.uk

① Introduction

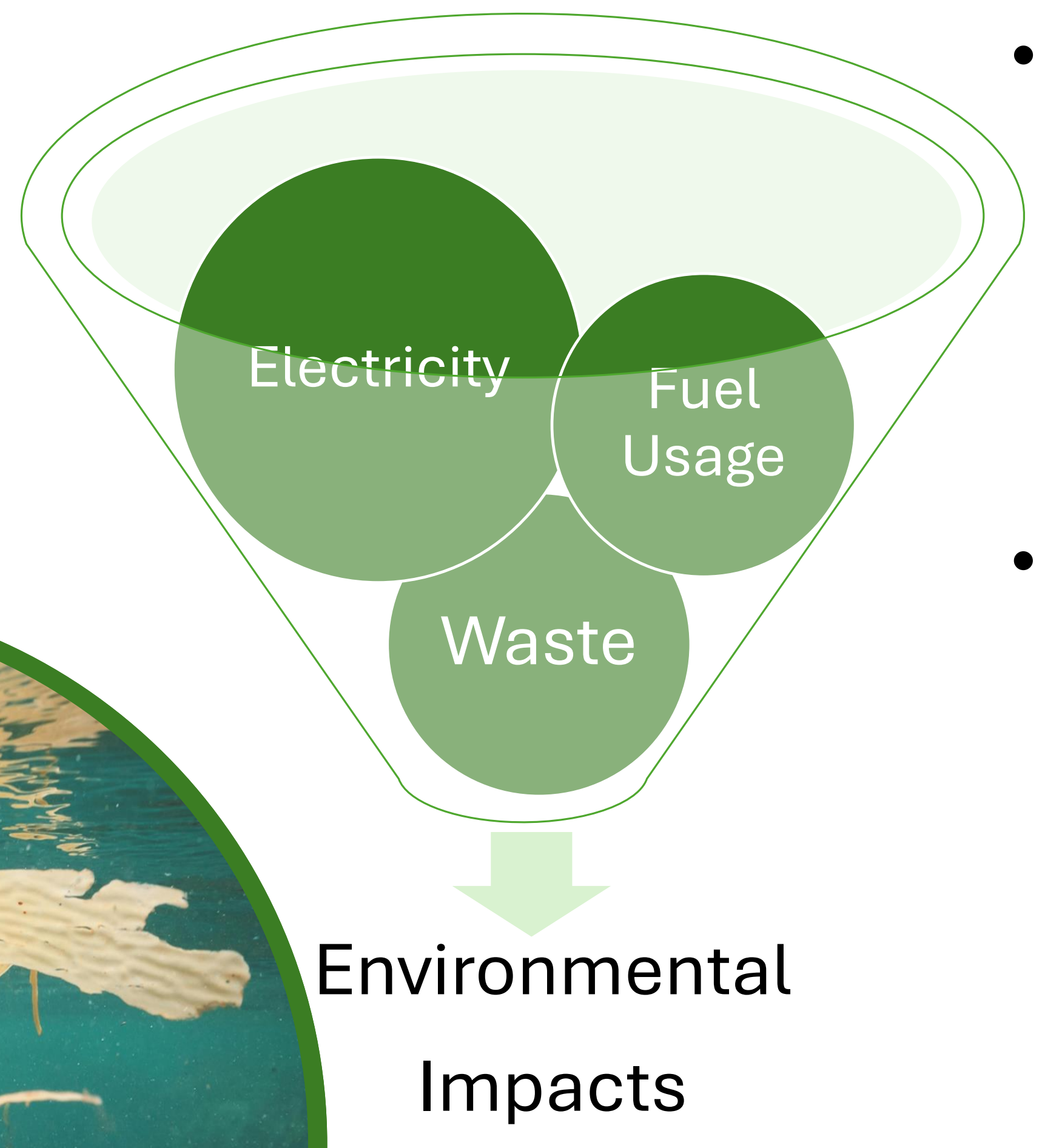
Project Aims:

This project aims to investigate the **environmental impacts** associated with **the production and utilisation of seaweed**

Research Questions:

1. How sustainable is **seaweed production** at **industrial scale?**
2. How can **seaweed valorisation** present **sustainable options** for future development?
3. How can the **LCA methodology** be adapted to **better apply to marine based research?**

② Environmental Impacts



- Environmental impacts are changes caused to the environment resulting from the **seaweed production and use life cycle**
- Common impact categories include **global warming, ecotoxicity** and **eutrophication** but **marine focused impacts** may be **more suitable for research** (1)

③ Why Farmed Seaweed?

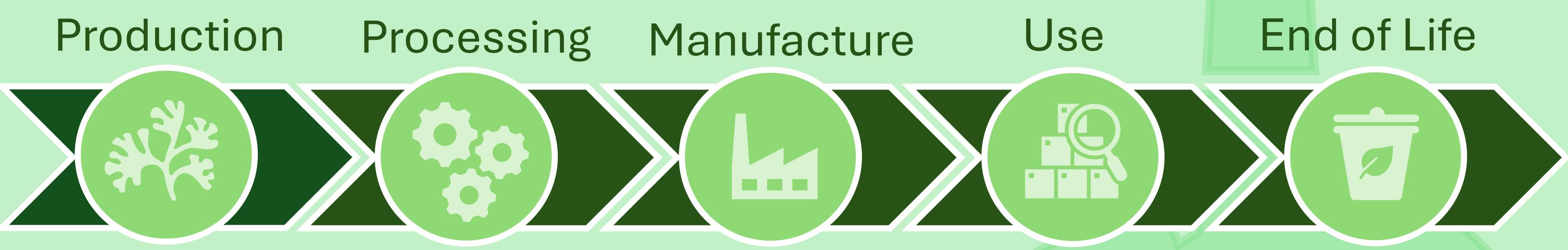
1. Seaweed has some **advantages over terrestrial crops** (2) leading to **increased demand**
2. UK production is dominated by **wild harvesting**, but demand increases will cause a **shift in production methods**
3. Seaweed has **numerous uses** (3) including:

Food **Chemical** **Green Energy** **Building Materials** **Animal Feed**

More research is needed to avoid unforeseen consequences as the potential of seaweed is explored

④ The LCA Methodology

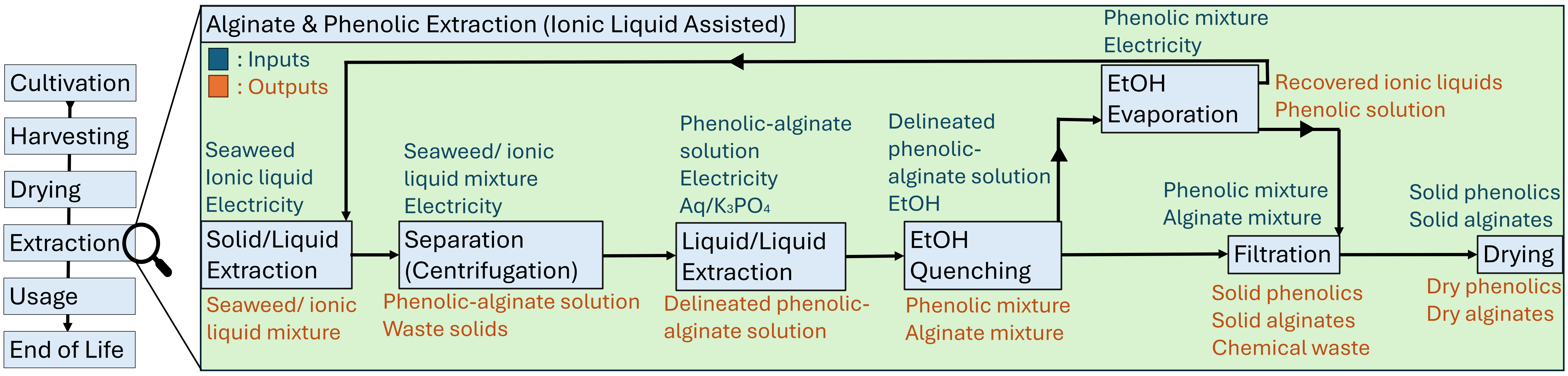
Life cycle analysis (LCA) quantifies a product's lifetime impact using a **four-step method**, ensuring a comprehensive evaluation **without burden shifting** while still allowing for **hotspot identification**



The project will also assess how **LCA variations can spotlight sustainability issues & ensure marine applicability** by assessing the use of **LCA variants** or **new impact categories**

⑤ Preliminary Results

Following a literature review & laboratory visit an initial modular LCA map was created detailing seaweed production & usage:



Cultivation
Harvesting
Drying
Extraction
Usage
End of Life

Alginate & Phenolic Extraction (Ionic Liquid Assisted)

🟦 : Inputs
🟧 : Outputs

Solid/Liquid Extraction
Inputs: Seaweed, Ionic liquid, Electricity
Outputs: Seaweed/ ionic liquid mixture

Separation (Centrifugation)
Inputs: Seaweed/ ionic liquid mixture, Electricity
Outputs: Phenolic-alginate solution, Waste solids

Liquid/Liquid Extraction
Inputs: Phenolic-alginate solution, Electricity, Aq/K_3PO_4
Outputs: Delineated phenolic-alginate solution

EtOH Quenching
Inputs: Delineated phenolic-alginate solution, EtOH
Outputs: Phenolic mixture, Alginate mixture

EtOH Evaporation
Inputs: Phenolic mixture, Electricity
Outputs: Recovered ionic liquids, Phenolic solution

Filtration
Inputs: Phenolic mixture, Alginate mixture
Outputs: Solid phenolics, Solid alginates, Chemical waste

Drying
Inputs: Solid phenolics, Solid alginates
Outputs: Dry phenolics, Dry alginates

Figure 1: An LCA map of unit processes involved in alginate and phenolic extraction via the usage of ionic liquids. Inputs to each process are shown in blue while outputs are in orange

Using this process map for chemical extraction an initial LCA was completed, assessing process sustainability at a lab scale:

- The LCA assumed the exclusion buildings & machinery and a typical Irish grid mix of electricity (sourced from Sima Pro)
- The following graph compares the global warming potential scores for 4 different alginate green extraction processes
- All results have been scaled to the functional unit (1kg of Seaweed)
- Results highlight the potential of ionic liquids to be a green dual extraction methodology (extracting both alginate & phenolics)

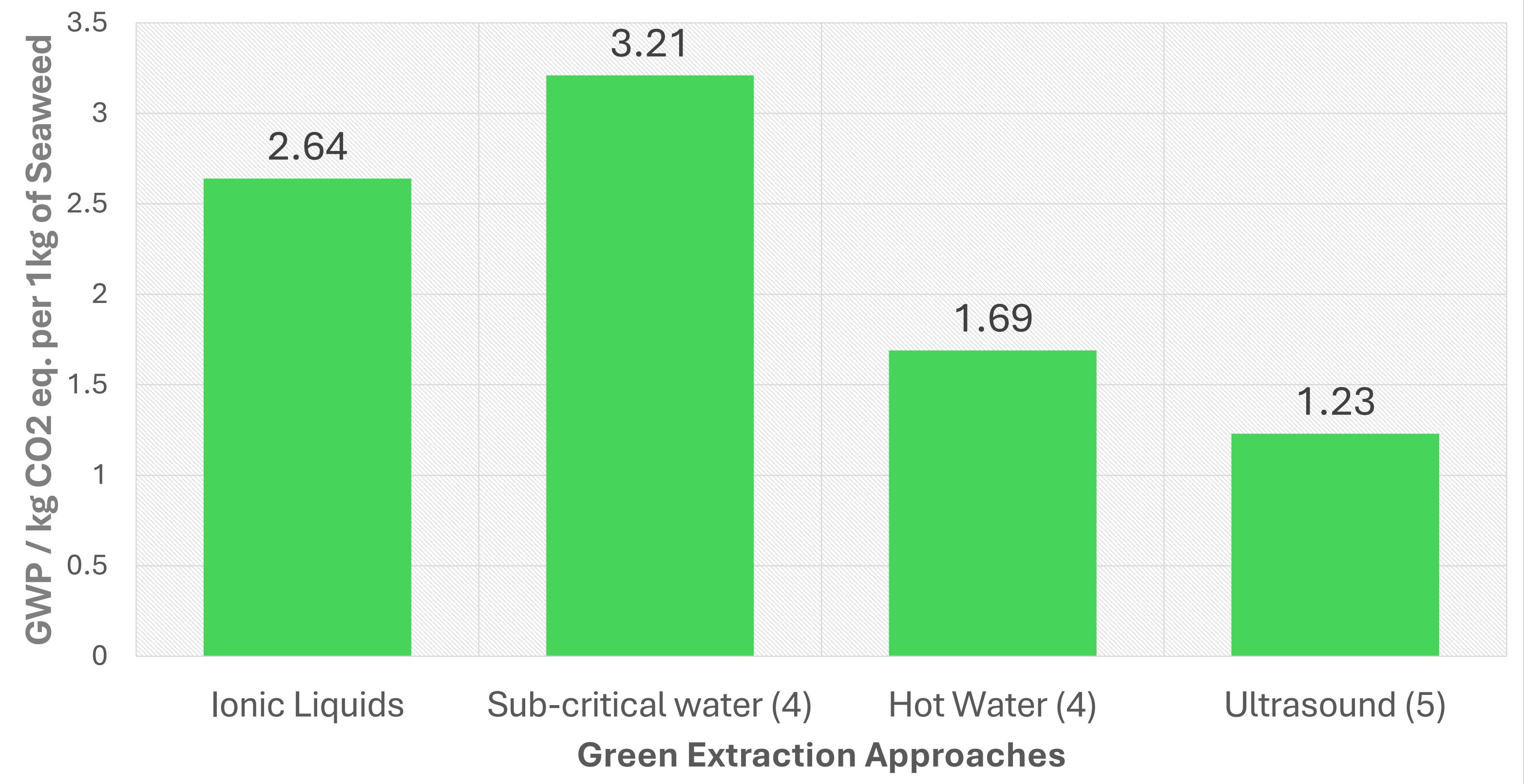
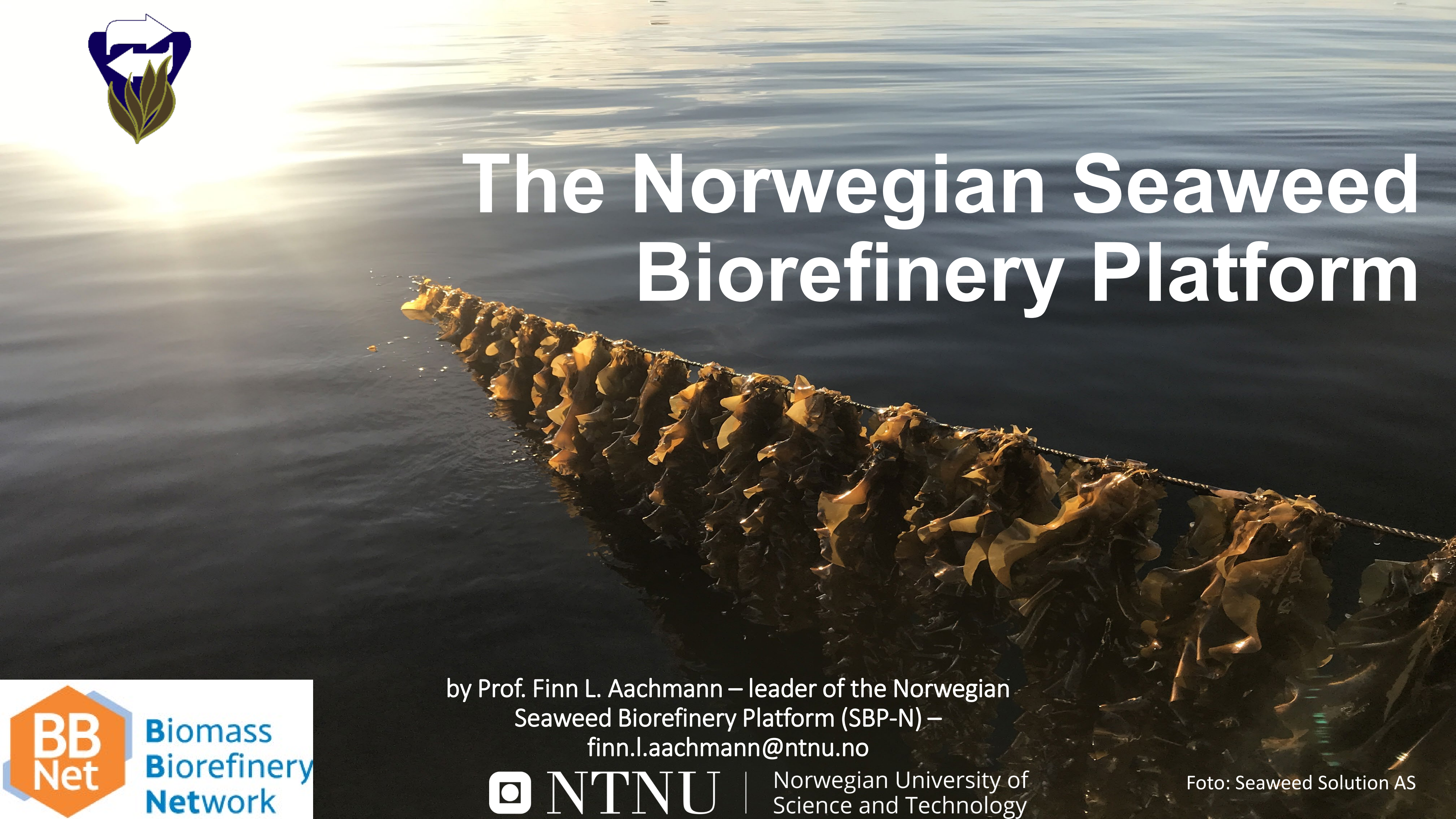


Figure 2: A graph highlighting GWP impact results for four different green extraction methodologies

(1) Woods, J. S., Veltman, K., Huijbregts, M. A. J., Verones, F., & Hertwich, E. G. (2016). Towards a meaningful assessment of marine ecological impacts in life cycle assessment (LCA). In *Environment International* (Vols. 89–90, pp. 48–61). Elsevier Ltd. https://doi.org/10.1016/j.envint.2015.12.033
(2) Spillias, S., Valin, H., Batka, M., Sperling, F., Havlík, P., Leclère, D., Cottrell, R. S., O'Brien, K. R., & McDonald-Madden, E. (2023). Reducing global land-use pressures with seaweed farming. *Nature Sustainability*, *6*(4), 380–390. https://doi.org/10.1038/s41893-022-01043-y
(3) Zhang, L., Liao, W., Huang, Y., Wen, Y., Chu, Y., & Zhao, C. (2022). Global seaweed farming and processing in the past 20 years. In Food Production, Processing and Nutrition (Vol. 4, Issue 1). BioMed Central Ltd. https://doi.org/10.1186/s43014-022-00103-2
(4) Zhang, X., Border, A., Goosen, N., & Thomsen, M. (2021). Environmental life cycle assessment of cascade valorisation strategies of South African macroalga Ecklonia maxima using green extraction technologies. *Algal Research*, *58*, 102348. https://doi.org/10.1016/J.ALGAL.2021.102348
(5) Ummat, V., Sivagnanam, S. P., Rameshkumar, S., Pednekar, M., Fitzpatrick, S., Rai, D. K., Padamati, R. B., O'Donnell, C., & Tiwari, B. K. (2024). Sequential extraction of fucoidan, laminarin, mannitol, alginate and protein from brown macroalgae Ascophyllum nodosum and Fucus vesiculosus. *International Journal of Biological Macromolecules*, *256*, 128195. https://doi.org/10.1016/J.IJBIOMAC.2023.128195

PDF HERE



The Norwegian Seaweed Biorefinery Platform

by Prof. Finn L. Aachmann – leader of the Norwegian Seaweed Biorefinery Platform (SBP-N) – finn.l.aachmann@ntnu.no

NTNU | Norwegian University of Science and Technology

BB Net Biomass Biorefinery Network

Foto: Seaweed Solution AS

Historical use of seaweed in Norway

Cultivated seaweed
A sustainable resource

4th *era*
2020s

The era of science

3rd *era*
1960s

~180 000 ton/Y
Polysaccharides
for food, industrial and medical application

mapping our national resources (after WWII)

1950s

Norsk institutt for tang- og tareforsking (NITT)

Kelp meal

2nd *era*
1930s

~20 000 ton/Y
Feed supplements
Fertilizer

Industrial need for minerals (e.g. glass, gun powder)

1st *era*
1750s

Kelping
~200 000 ton/Y
Soda, Iodine,
'saltpeter'

In need of better

Feed and Food
Fertilizer
Fuel


Photo: Schrøder/Sverresborg Trøndelag Folkemuseum

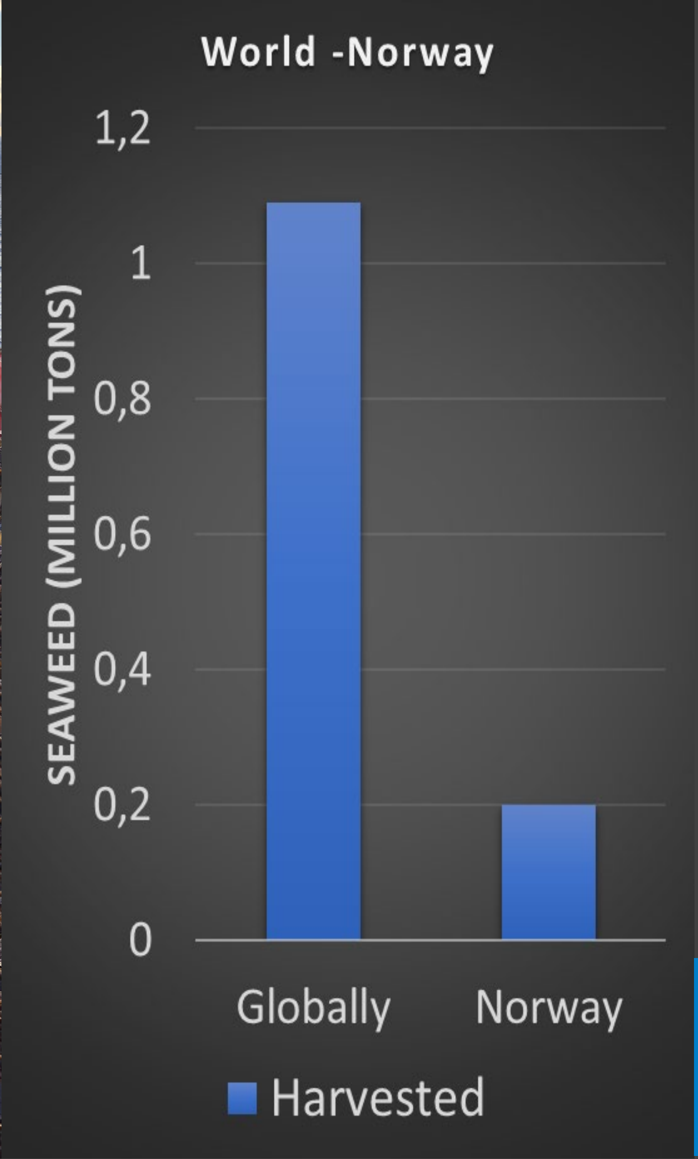

Olav Smidsrød


Jæren (1910)

http://gardsdrift.no/tang-og-tare-i-sauef%C3%B4ret

Østgaard, K og Indergaard, M Naturen (2017), *Vår historiske bruk av tang og tare.* 141, p.194-206

Seaweed industry in Norway – wild collected seaweed



Wild collected seaweed in Norway

Ascophyllum nodosum

Process ~20 -30 000 tons harvested seaweed annually for feed ingredients and agriculture uses. Annual turnover ~180 million NOK

ALGEA The Arctic Company

Polar Algae

Laminaria hyperborea

In Norway: ~150 000 tons of harvested seaweed annually for alginate production. >600 applications and export 1 Billion NOK.

> 50 mill ton of *L. hyperborea* in Norway

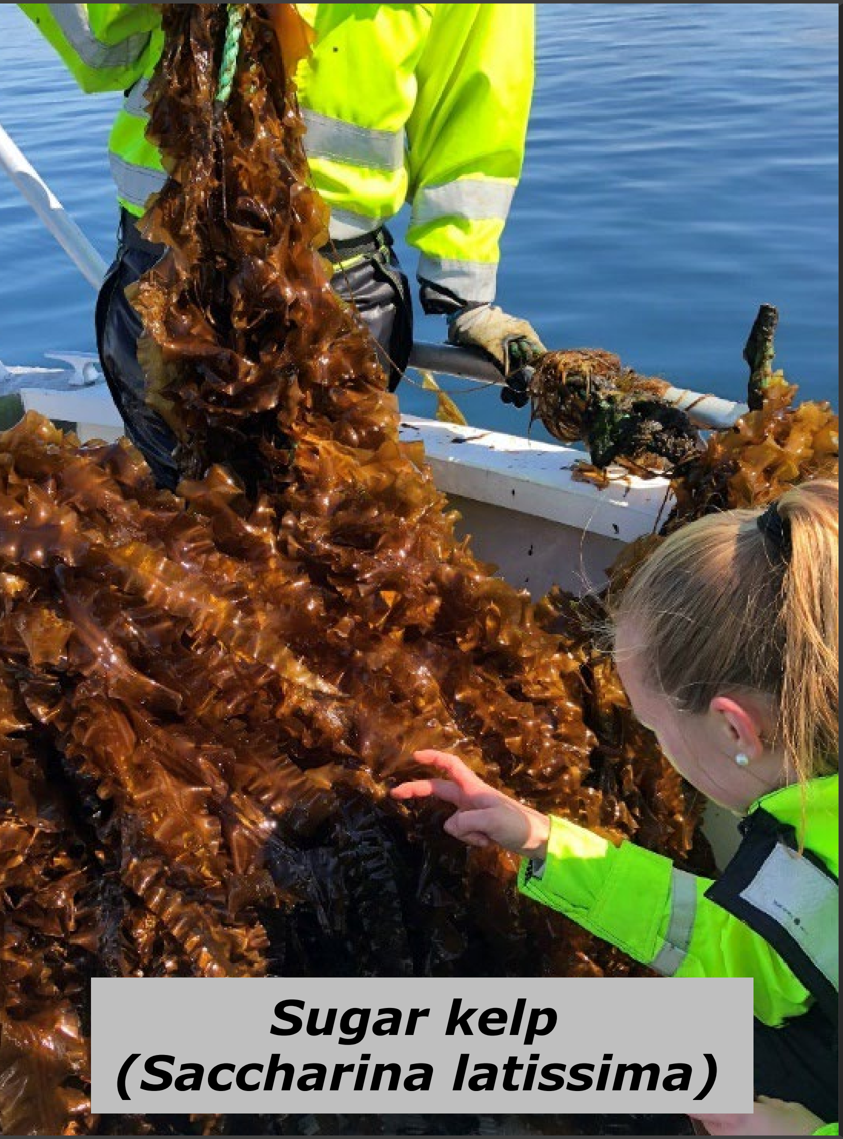
iff

nutrimar

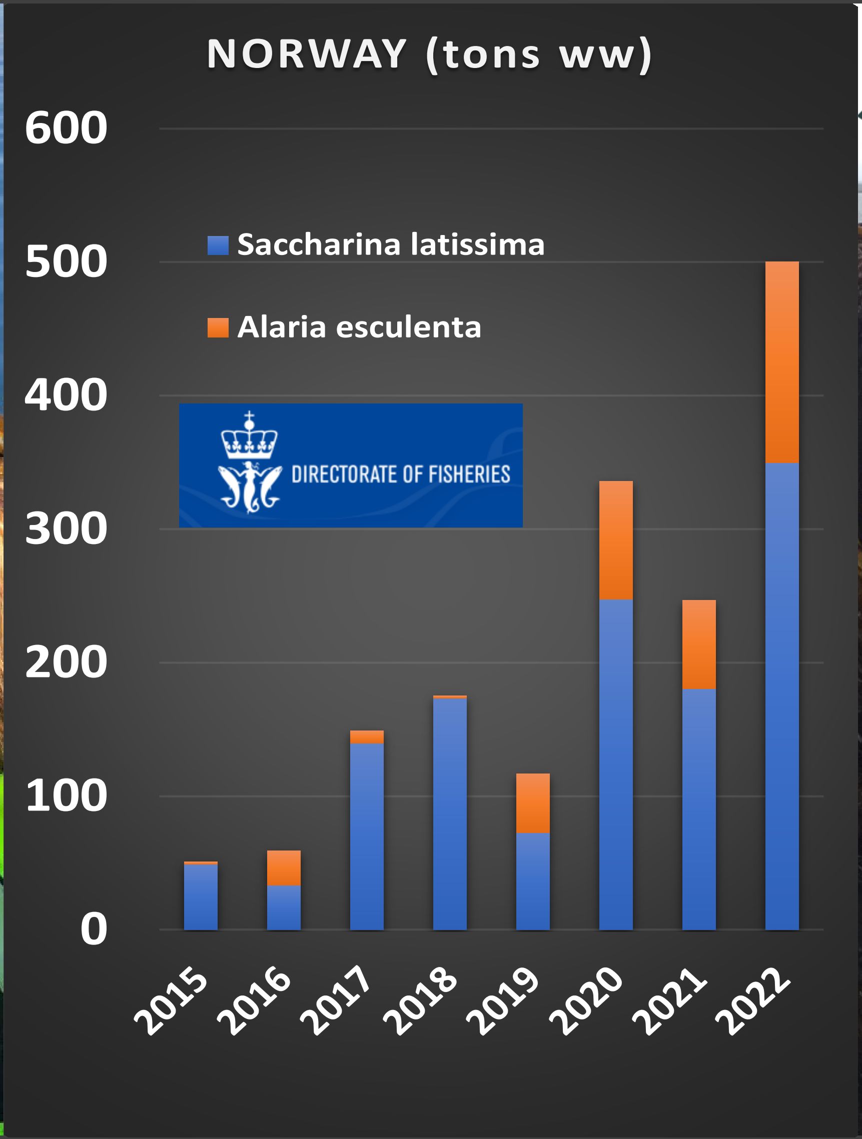
alginor

Norwegian utilisation represent 15-20% global wild harvest

Seaweed industry in Norway – seaweed cultivation



Sugar kelp (Saccharina latissima)

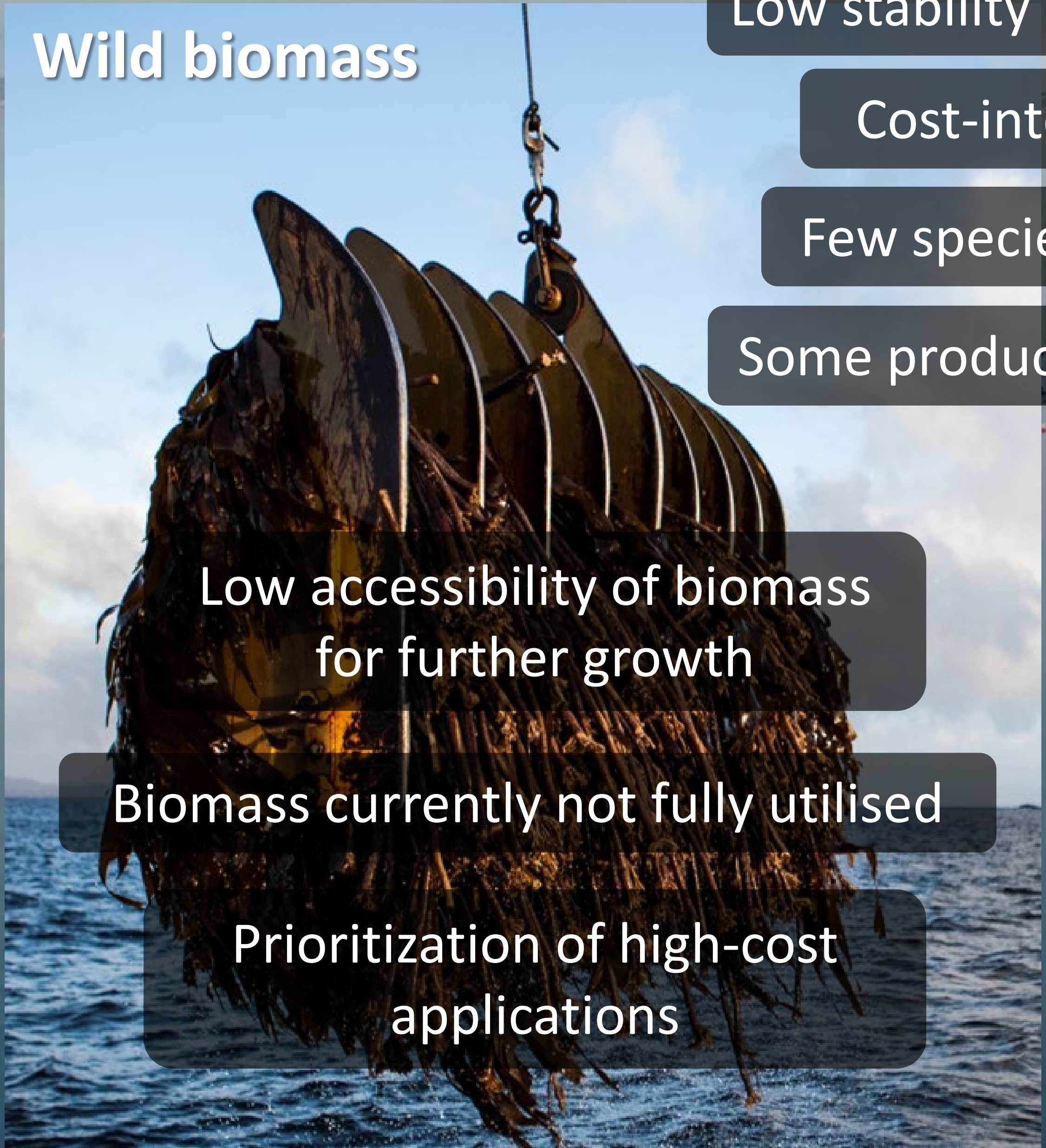


Winged kelp (Alaria esculenta)

The Norwegian cultivated seaweed industry is small but growing!

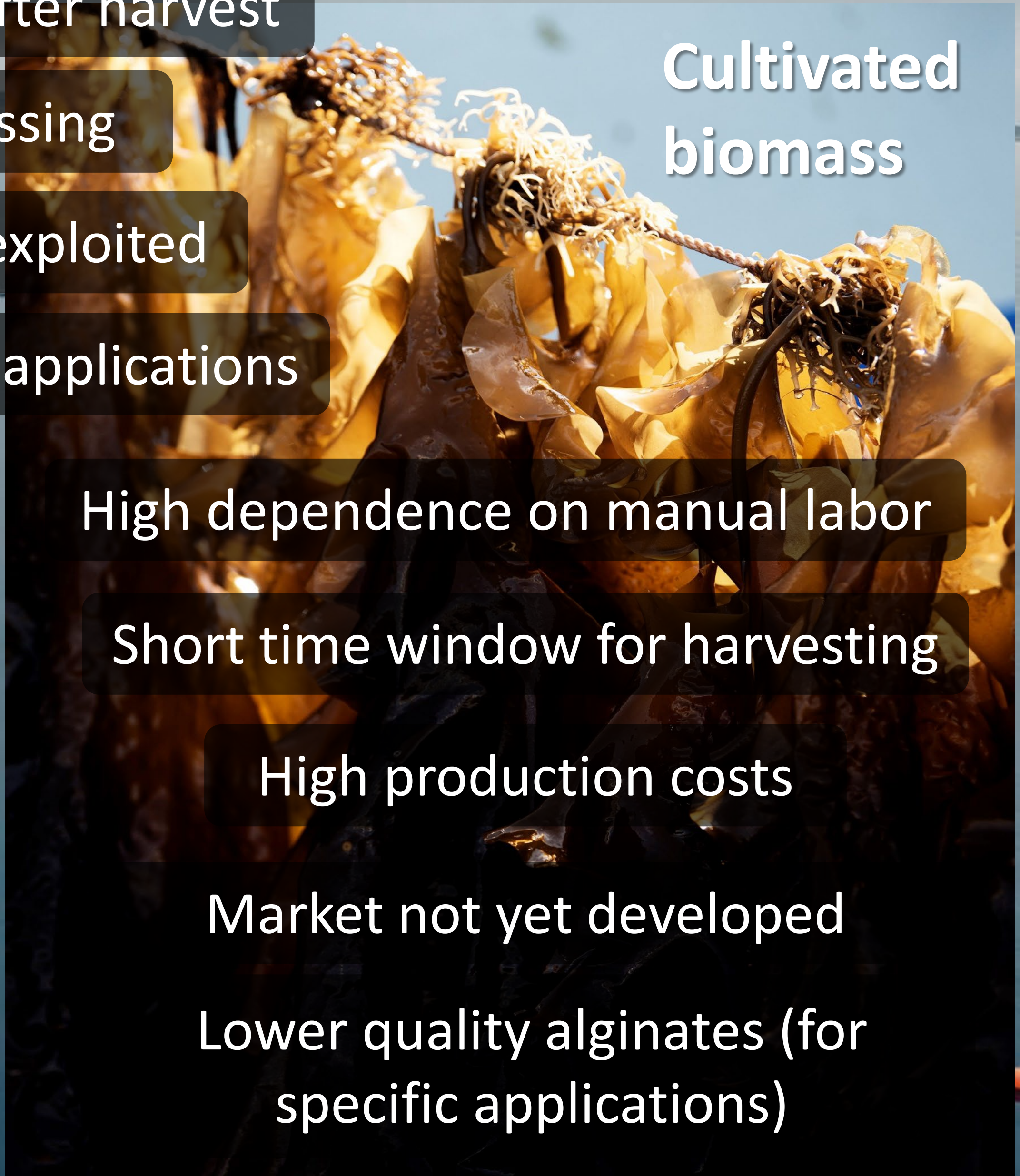
Challenges in seaweed value chains

- Low stability of biomass after harvest
- Cost-intensive processing
- Few species currently exploited
- Some products lack good applications



Wild biomass

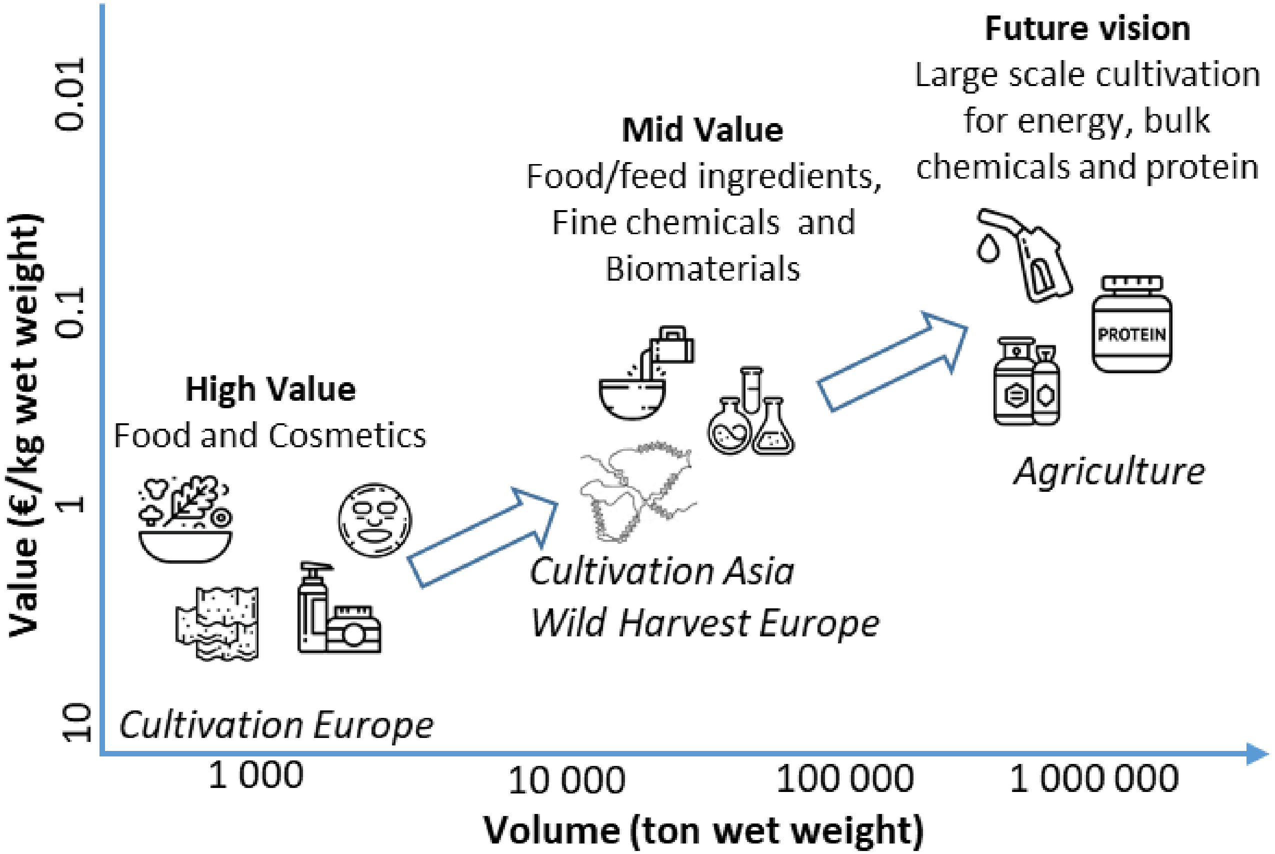
- Low accessibility of biomass for further growth
- Biomass currently not fully utilised
- Prioritization of high-cost applications



Cultivated biomass

- High dependence on manual labor
- Short time window for harvesting
- High production costs
- Market not yet developed
- Lower quality alginates (for specific applications)

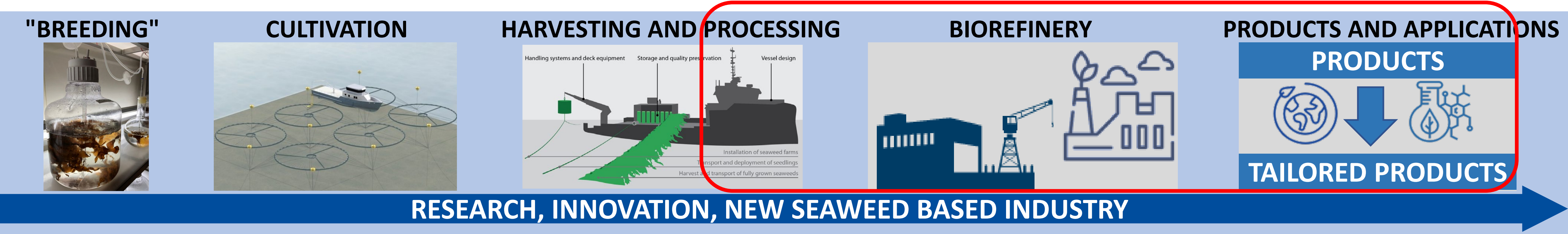
«Market roadmap»
From high value Food to industrial commodities



Industrialization of cultivation, harvest and processing necessary to reduce production cost

The supply of biomass must be high enough to enable a market pull

The Norwegian Biorefinery Platform SBP-N



"BREEDING"

CULTIVATION

HARVESTING AND PROCESSING

BIOREFINERY

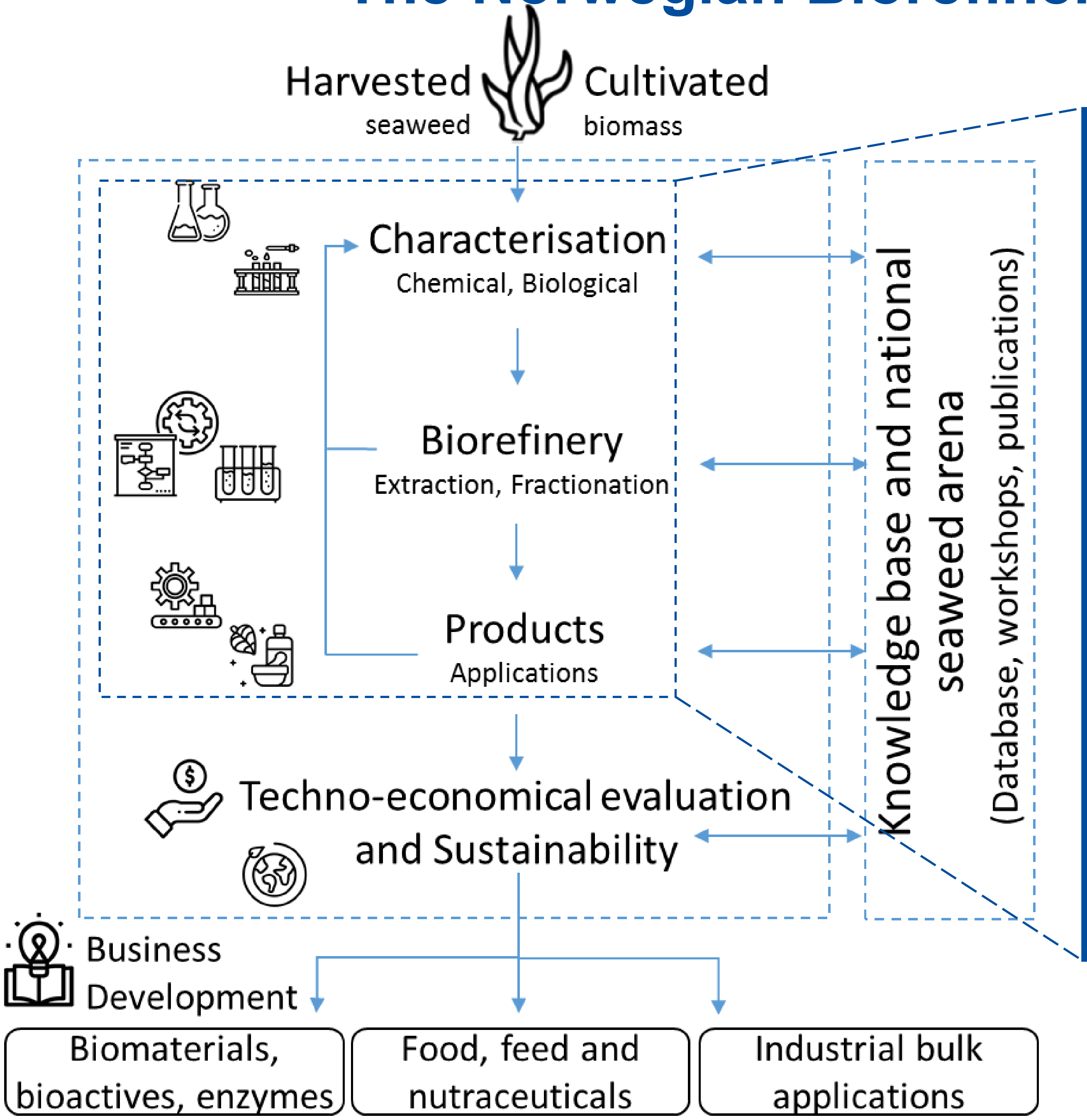
PRODUCTS AND APPLICATIONS

PRODUCTS

TAILORED PRODUCTS

RESEARCH, INNOVATION, NEW SEAWEED BASED INDUSTRY

The Norwegian Biorefinery Platform SBP-N



Harvested seaweed

Cultivated biomass

Characterisation
Chemical, Biological

Biorefinery
Extraction, Fractionation

Products
Applications

Techno-economical evaluation and Sustainability

Knowledge base and national seaweed arena
(Database, workshops, publications)

Business Development

Biomaterials, bioactives, enzymes

Food, feed and nutraceuticals

Industrial bulk applications

Made with Freepikcompany by flaticon.com

The platform serves as a hub for research, knowledge, methodology and stakeholder networks.

- ✓ SBP-N will aid in the regulation of macroalgae cultivation and harvesting industries, and in the characterization of macroalgae-derived products.
- ✓ Focus on characterizing biomass, advancing technology for sustainable biorefinery processes, and establishment of high-value and bulk product pipelines.

NMBU Norges miljø- og biovitenskapelige universitet

MØREFORSKING

Nofima

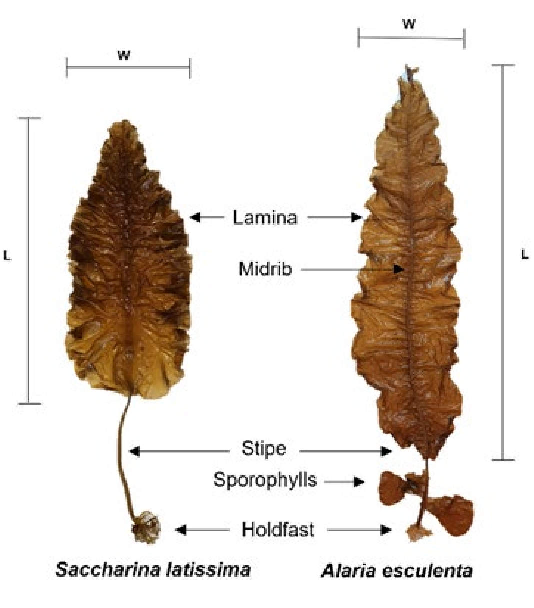
SINTEF

NTNU Norwegian University of Science and Technology

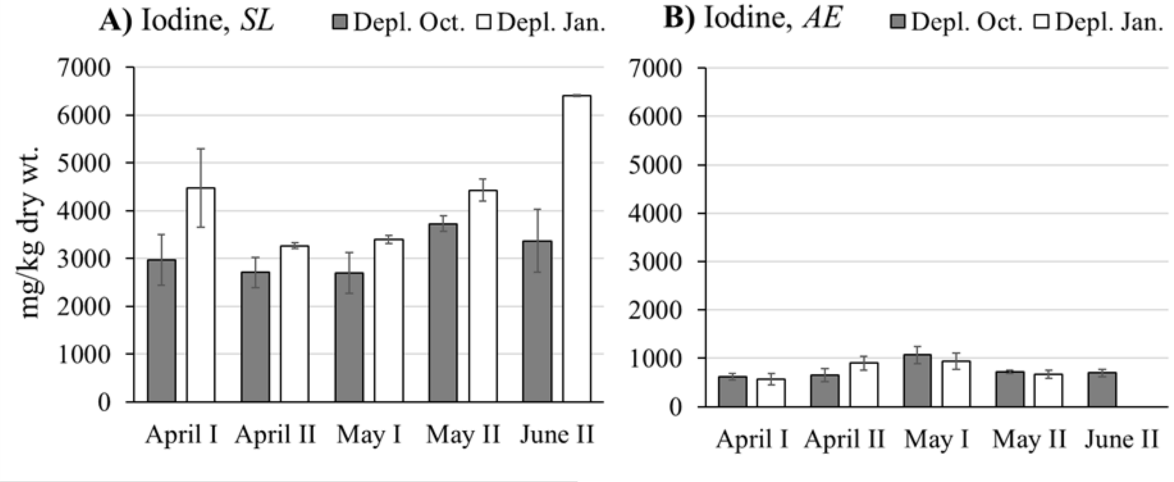
The Research Council of Norway

Case study 1: Understanding compositional changes in the biomass

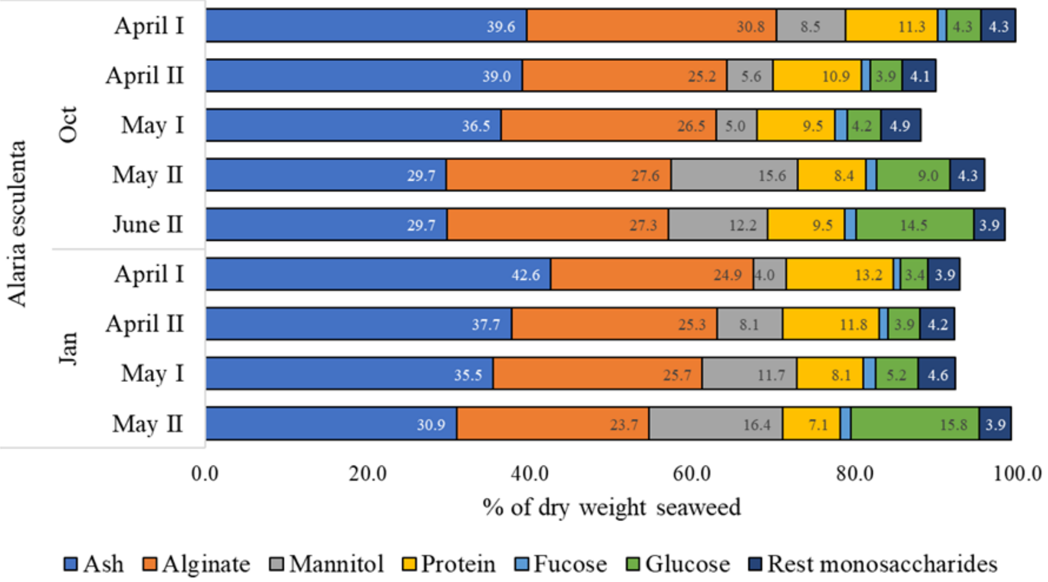
Changes in growth and composition of cultivated *Saccharina latissima (SL)* and *Alaria esculenta (AE)* at different deployment and harvesting times



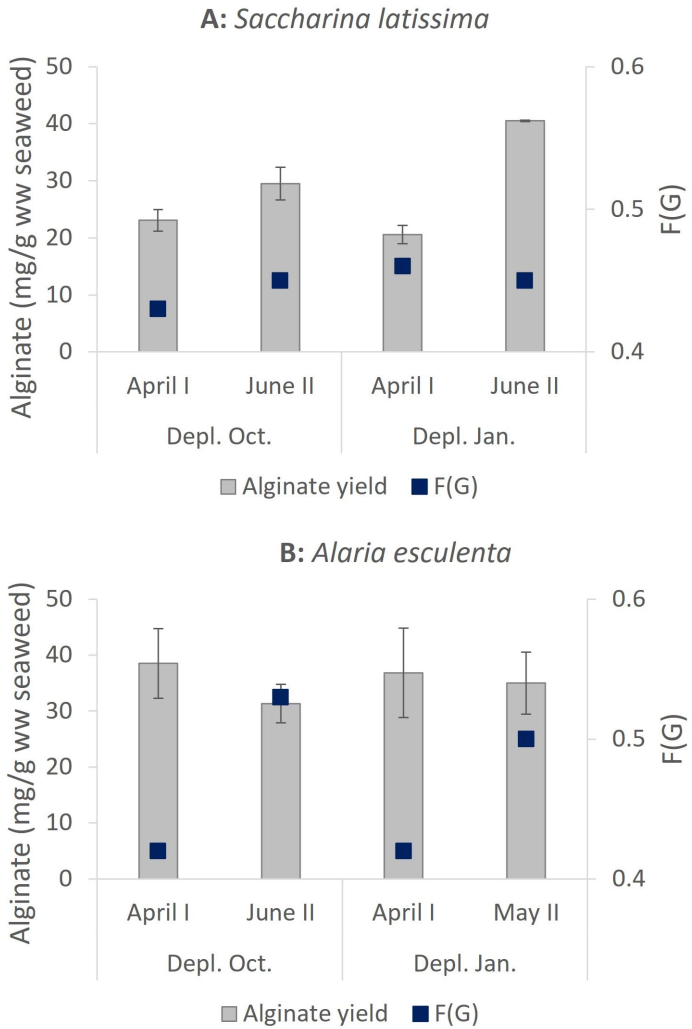
Arlov *et al.* 2024 Algal Res. Vol. 78, pp. 103421



***SL* Oct are lower in iodine, while *AE* are similar**



Mannitol and glucose (laminarin) displays a large variation over the harvesting season



F_G seems to be similar for *SL* while F_G increase during the harvesting season for AE

Case study 2: Solutions for Iodine Reduction


© Seaweed Solutions

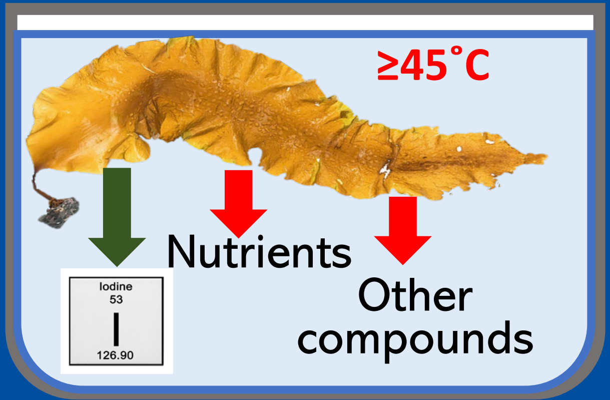
1. Laid on trays


© Seaweed Solutions

2. Short dip in hot water

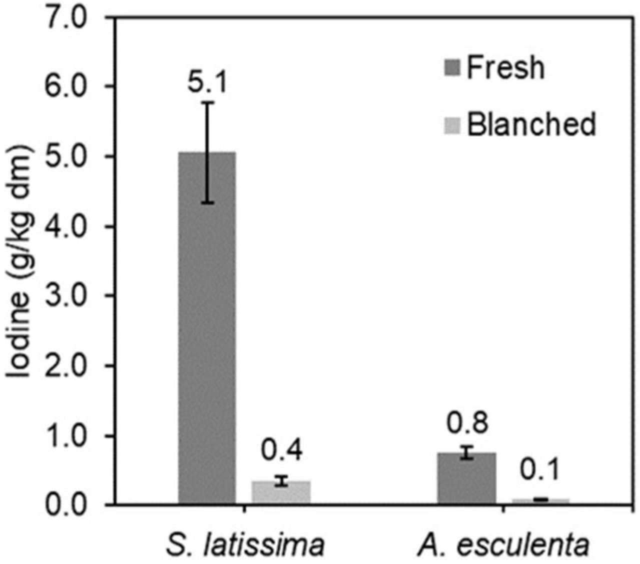

© Seaweed Solutions

3. cooled in water



How does different parameters affect the blanching process?

- ☐ Time and Temperature (45˚C 30s, 45˚C 120s, 80˚C 30s)
- ☐ Water : Seaweed ratio (500 g/L)
- ☐ Cut vs whole
- ☐ Fresh water vs Salt water (FWSW, SWSW, SWFW)
- ☐ Repeated blanching (Rep 5 – Rep10)



- ***SL*** **reduction from 5000 mg/kg to 250-800 mg/kg**
- ***AE*** **reduction from 700 mg/kg to 50-150 mg/kg**

(Standart 90% reduction)

(+) 80˚C, 30s favorable for ↓ microbiology and color

(-) water reduction reduce the blanching efficiency

( ) Minimal effect of cut vs whole

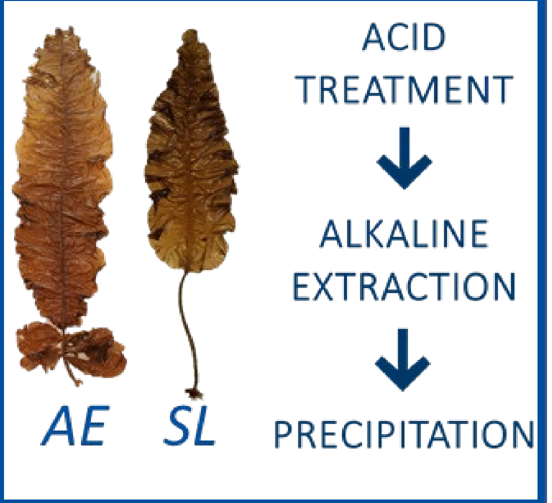
(+/-) Blanching in seawater led to a change in minerals

(+) Up to 10 times blanching in the same water display, minimal effect on iodine reduction

Case study 3: Establish alginate extraction for *AE* & *SL*

Norway produce alginate from Tangle ~7,000 Tons/Y

Aim to establish alginate extraction from cultivated seaweed


ACID TREATMENT

↓

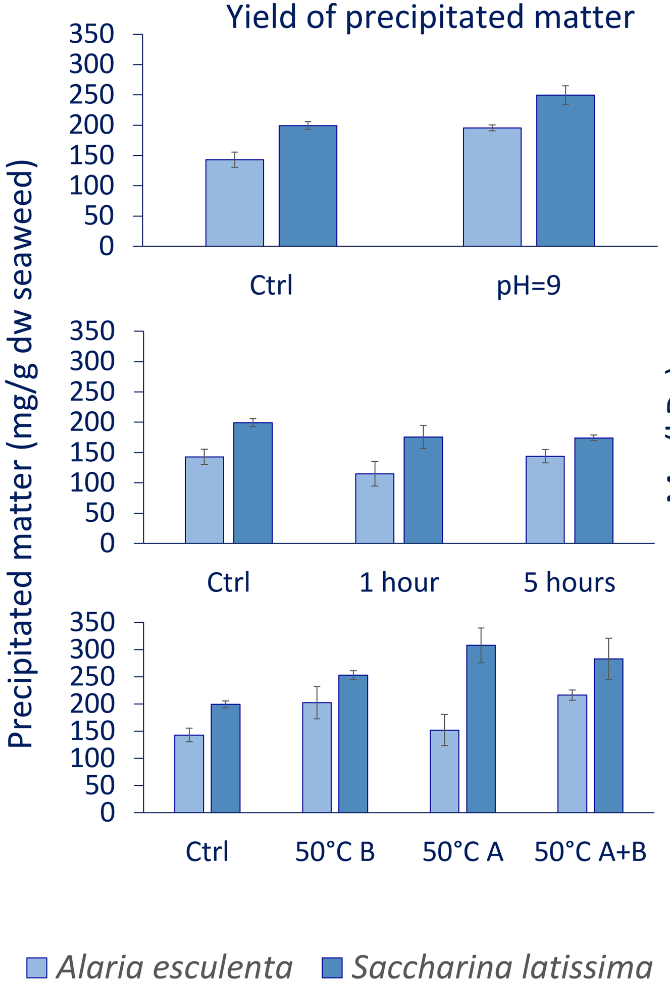
ALKALINE EXTRACTION

↓

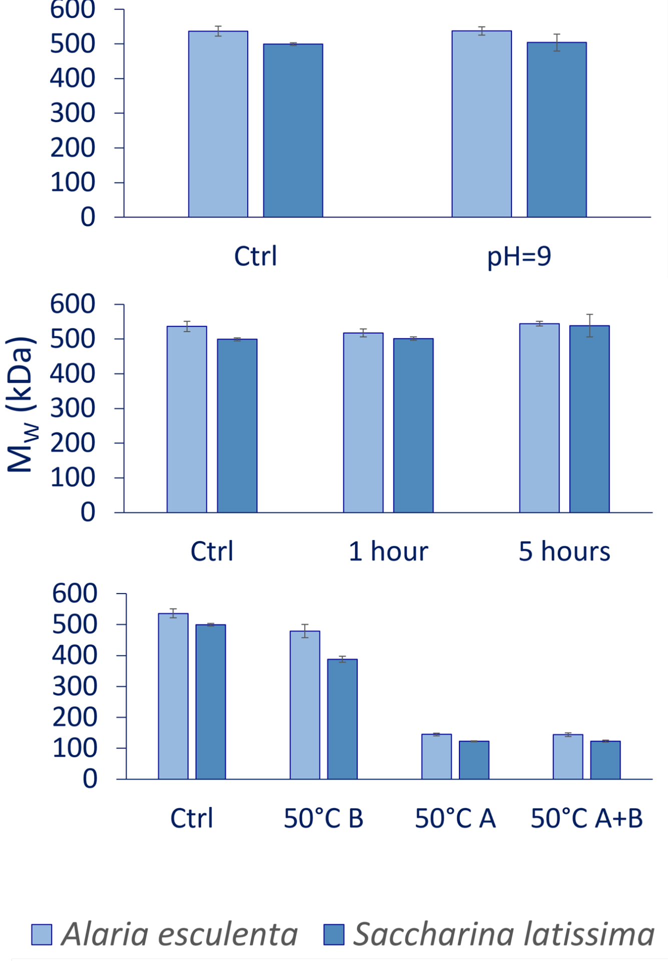
PRECIPITATION

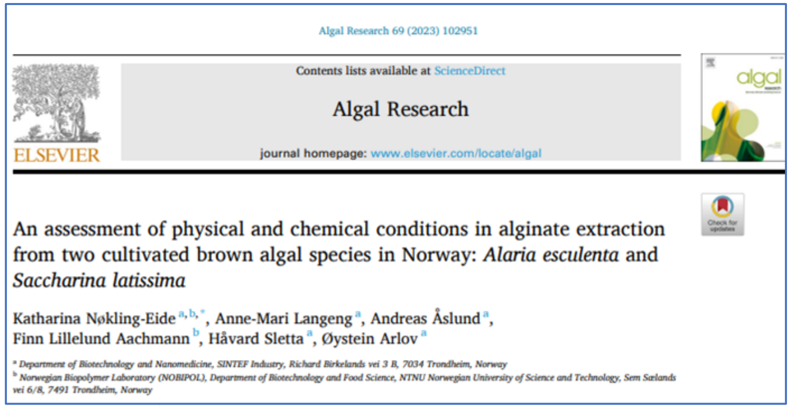
Tested parameters

pH, Extraction time, Temperature



Molecular weight




Algal Research 69 (2023) 102951

Contents lists available at ScienceDirect

Algal Research

journal homepage: www.elsevier.com/locate/algal

An assessment of physical and chemical conditions in alginate extraction from two cultivated brown algal species in Norway: *Alaria esculenta* and *Saccharina latissima*

Katharina Nøkling-Eide[a,b,*], Anne-Mari Langeng[a], Andreas Åslund[a], Finn Lillelund Aachmann[b], Håvard Sletta[a], Øystein Arlov[a]

[a] Department of Biotechnology and Nanomedicine, SINTEF Industry, Richard Birkelands vei 3 B, 7034 Trondheim, Norway

[b] Norwegian Biopolymer Laboratory (NOBIPOL), Department of Biotechnology and Food Science, NTNU Norwegian University of Science and Technology, Sem Sælands vei 6/8, 7491 Trondheim, Norway

- ✓ **Alginates with high yield and quality**
- ✓ **pH 9 increase with minimal impact on Mw**
- ✓ **Short Extraction time (1 hour)**
- ✓ **Temperature have a negative effect on Mw**

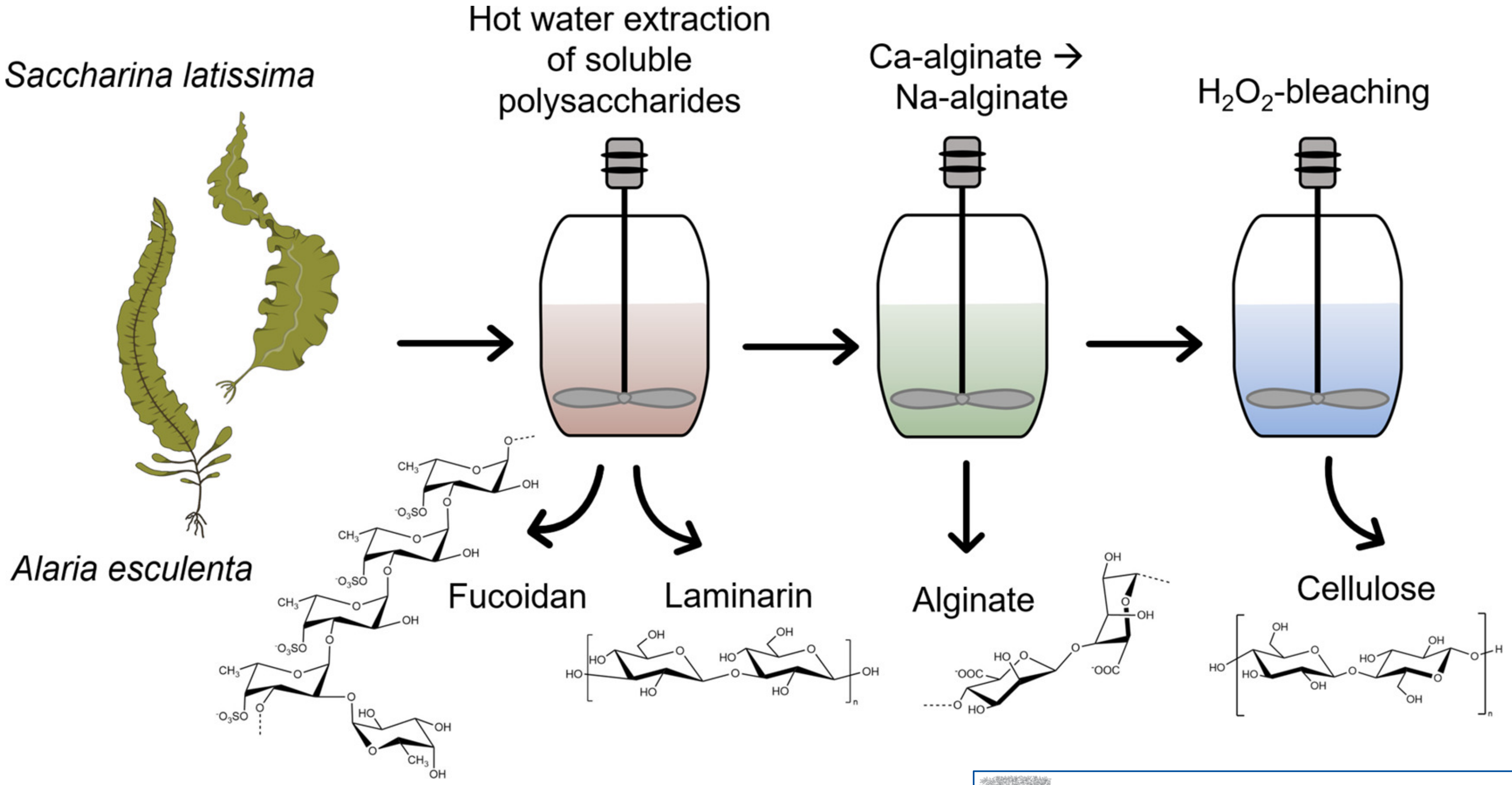
Case study 4: Biorefinery for polysaccharides from cultivated seaweed

Aim: Sequential extraction of laminarin, fucoidan, alginate and cellulose

Hot Water Extration
Fucoidan
Laminarin

ACID TREATMENT
↓
ALKALINE EXTRACTION
↓
PRECIPITATION

Bleaching
Cellulose



Extraction of Fucoidan, Laminarin without compromising Alginates (while Cellulose is stable)

ELSEVIER

Algal Research
Volume 69, January 2023, 102928

Sequential extraction and fractionation of four polysaccharides from cultivated brown algae *Saccharina latissima* and *Alaria esculenta*

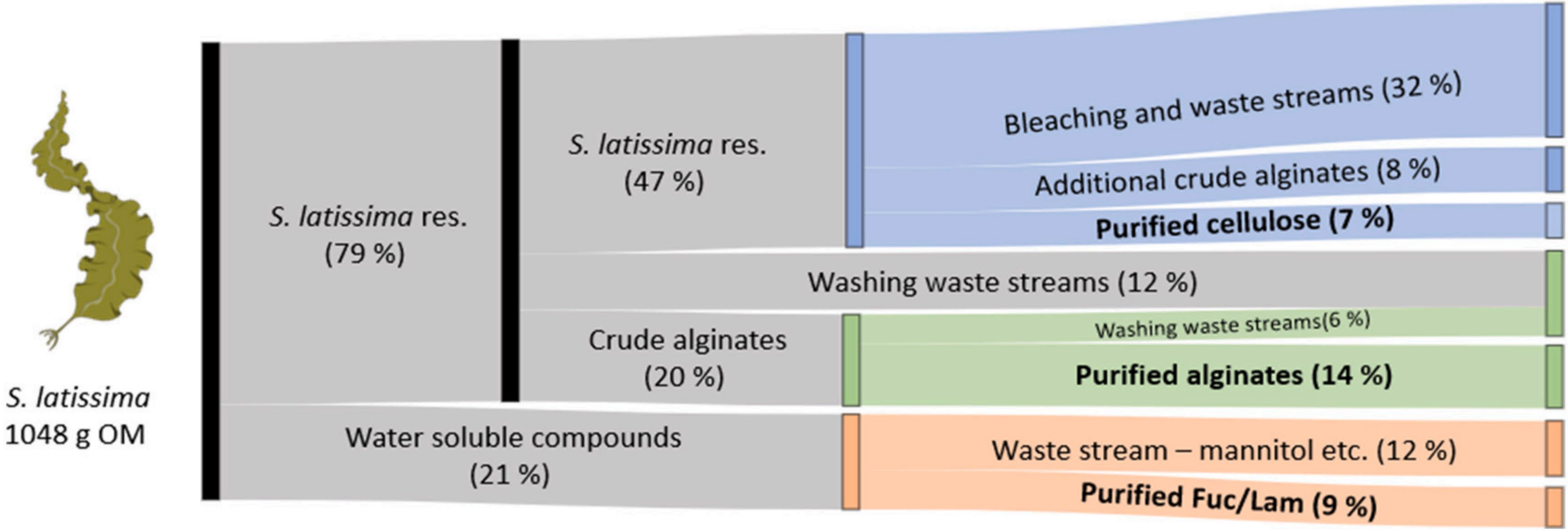
Paulina S. Birgersson [a], Maren Oftebro [a], Wenche I. Strand [a], Olav A. Aarstad [a], Gerd Inger Sætrom [a], Håvard Sletta [b], Øystein Arlov [b], Finn Lillelund Aachmann [a]

Case study 4: Sequential extraction and fractination

All fractions have high purity (<95%)

	Fucoidan/Laminarin		Alginate		Cellulose		Total	
	(g)	(% dw)	(g)	(% dw)	(g)	(% dw)	(g)	(% dw)
SL	80	5.0	172.6	10.76	111.2	6.9	375.2	23.4
AE	223.5	9.5	166.5	7.085	228.9	9.7	618.9	26.3

Possible with only chemical extraction



S. latissima
1048 g OM

S. latissima res.
(79 %)

S. latissima res.
(47 %)

Crude alginates
(20 %)

Water soluble compounds
(21 %)

Bleaching and waste streams (32 %)

Additional crude alginates (8 %)

Purified cellulose (7 %)

Washing waste streams (12 %)

Washing waste streams(6 %)

Purified alginates (14 %)

Waste stream – mannitol etc. (12 %)

Purified Fuc/Lam (9 %)

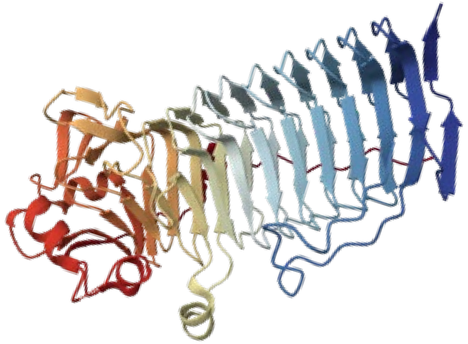
Fucoidan with high Mw

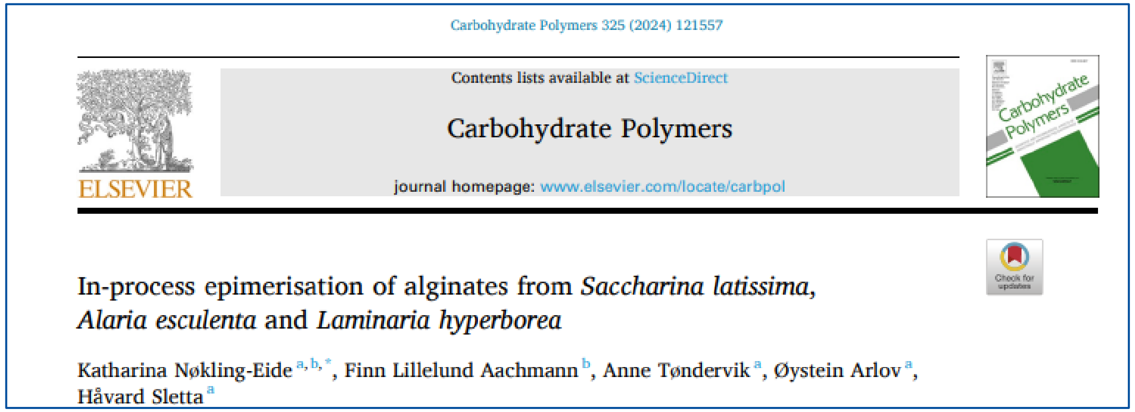
Laminarin

Alginates with high quality

Bleaching of cellulose works well

Case study 5: In-process epimerisation





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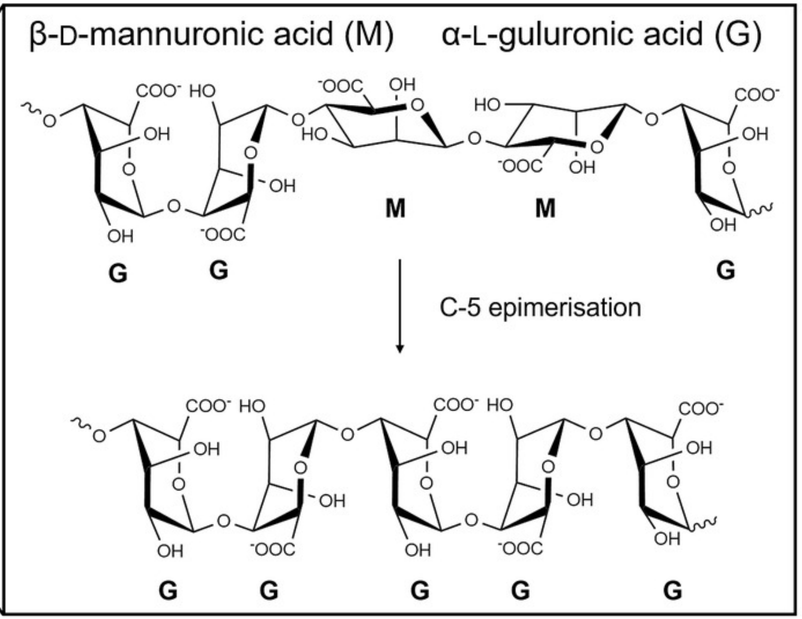
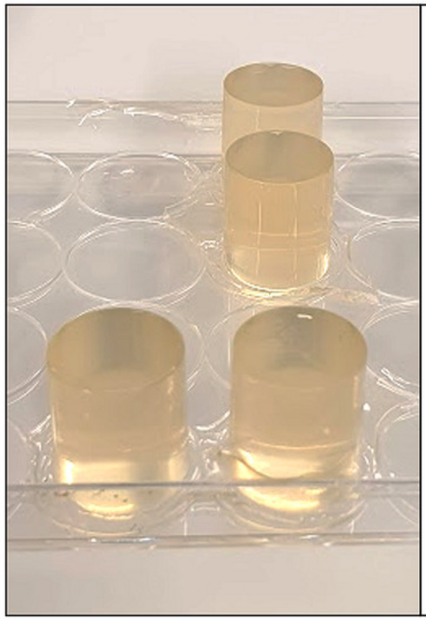
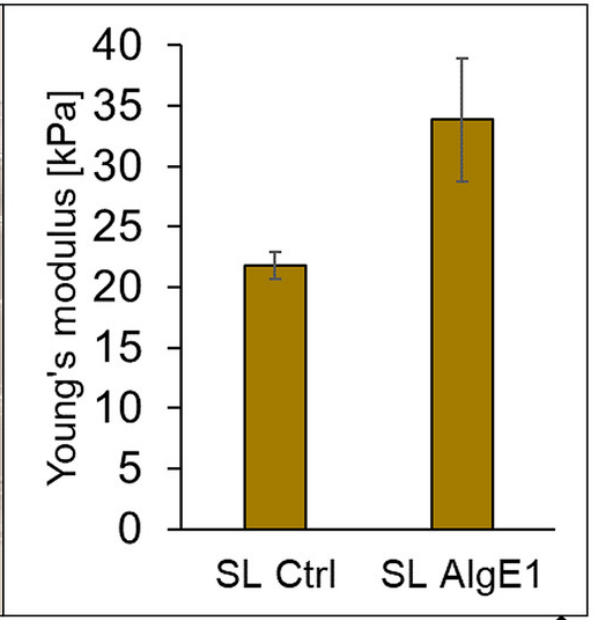
In-process epimerisation of alginates from *Saccharina latissima*, *Alaria esculenta* and *Laminaria hyperborea*

Katharina Nøkling-Eide [a,b,*], Finn Lillelund Aachmann [b], Anne Tøndervik [a], Øystein Arlov [a], Håvard Sletta [a]







Saccharina latissima (SL)
Alaria esculenta (AE)
Laminaria hyperborea (LH)

AlgE1 C-5 epimerase

In-process epimerization

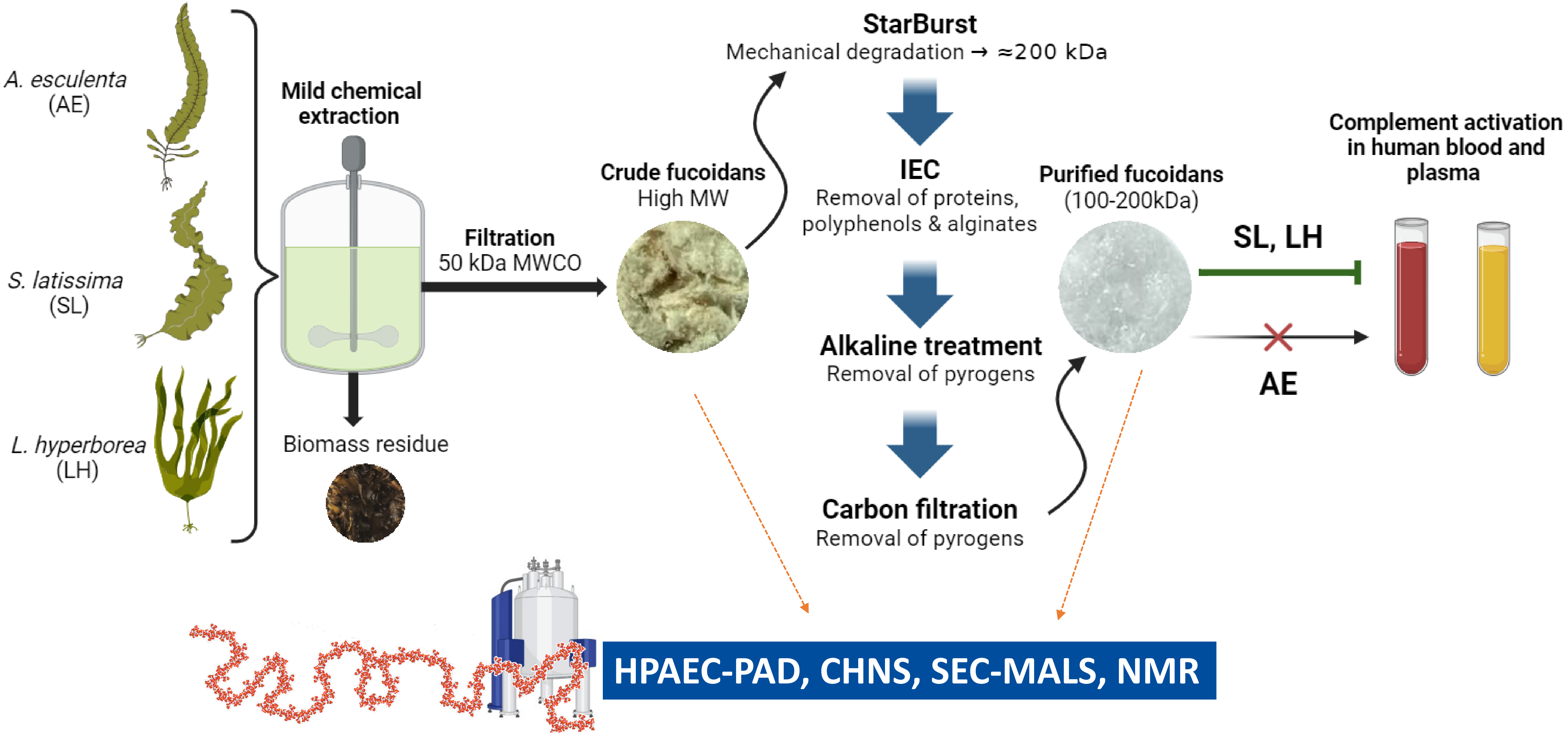
Alginate extraction

Structural characterization of alginates

SL F_G 0.46→0.76
AE F_G 0.53→0.61
LH F_G 0.46→0.57

Rheological characterization of alginate hydrogels

Case study 6: Chemical and structural assessment and bioactivity of fucoidans from SL, AE, LH



A. esculenta (AE)

S. latissima (SL)

L. hyperborea (LH)

Mild chemical extraction

Biomass residue

Filtration
50 kDa MWCO

Crude fucoidans
High MW

StarBurst
Mechanical degradation → ≈200 kDa

IEC
Removal of proteins, polyphenols & alginates

Alkaline treatment
Removal of pyrogens

Carbon filtration
Removal of pyrogens

Purified fucoidans
(100-200kDa)

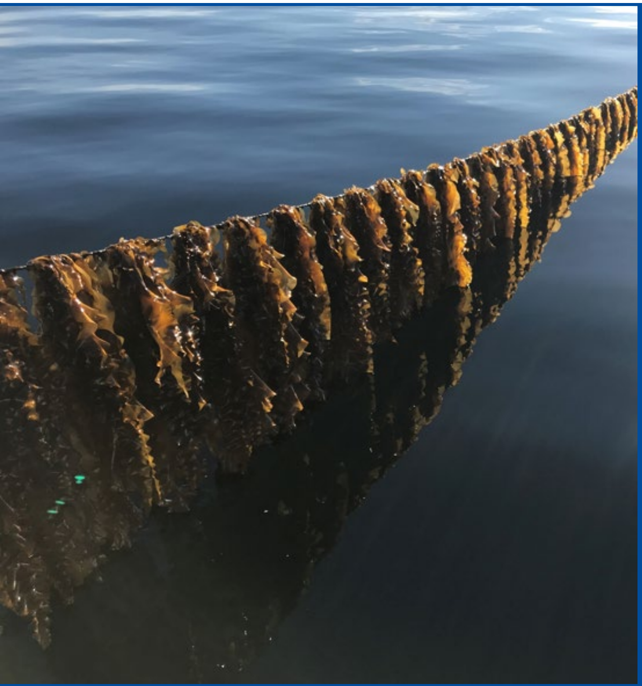
SL, LH

AE

Complement activation in human blood and plasma

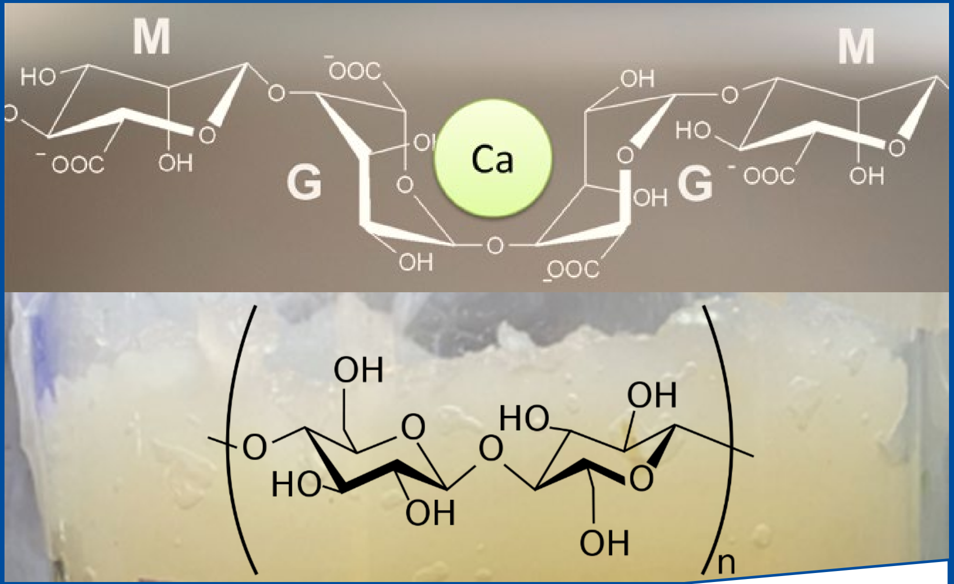
HPAEC-PAD, CHNS, SEC-MALS, NMR

Case study 7: Bioplastic from seaweed



Cultivated and wild brown algae, and residual biomass

Cost-effective alginate and cellulose extraction in pure fractions and crude, low-cost fractions



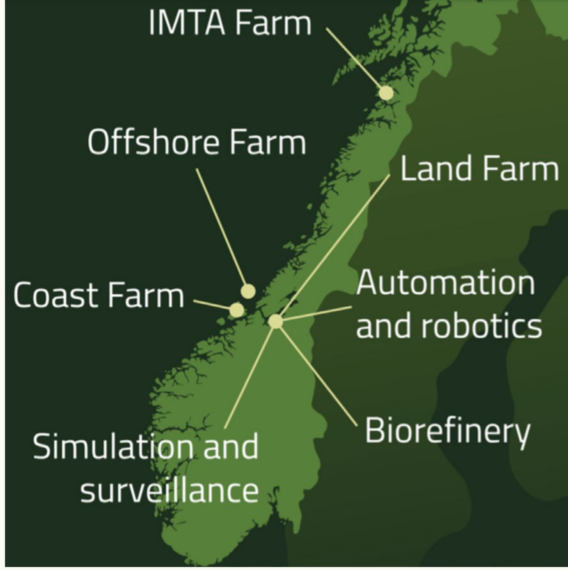
Purity + Processing costs

Assess effects of polysaccharide structure and fraction purity on material properties

Development of material prototypes and demonstration of pilot scale manufacturing

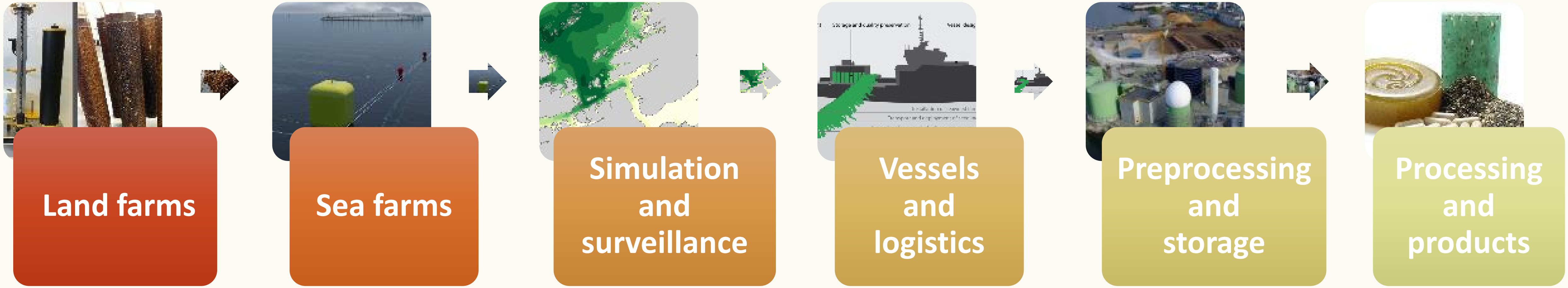
Norwegian
Seaweed
Centre

https://norsktaresenter.no/



RI SEAWEED

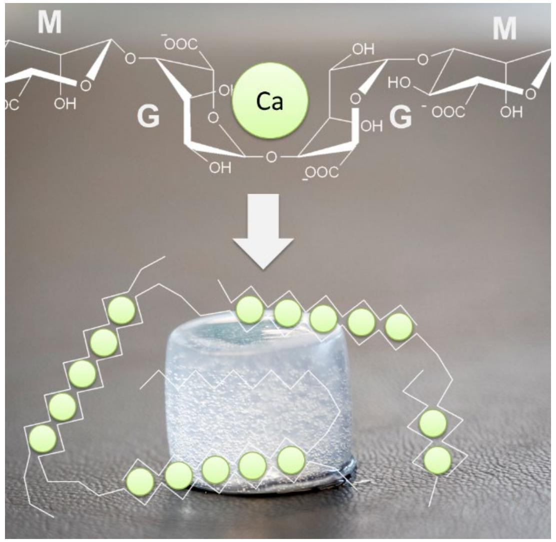
Norwegian Test Center for Seaweed Cultivation and Utilization Technologies



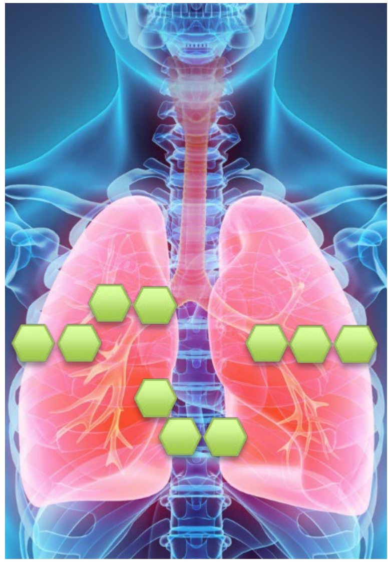
- Land farms
- Sea farms
- Simulation and surveillance
- Vessels and logistics
- Preprocessing and storage
- Processing and products

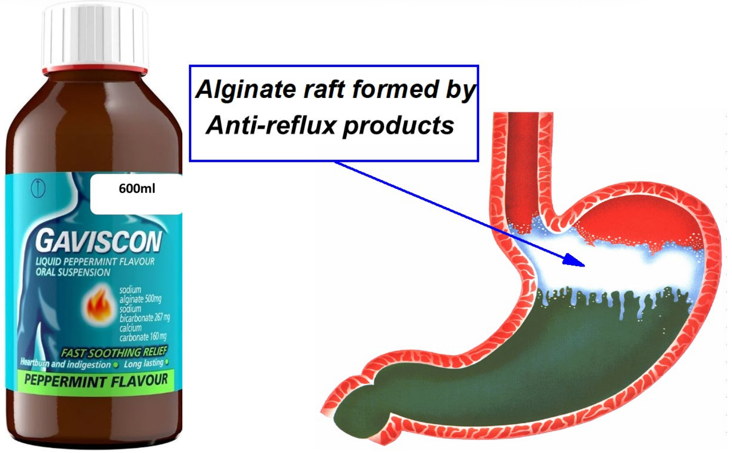
SINTEF NTNU

Alginate-based innovations



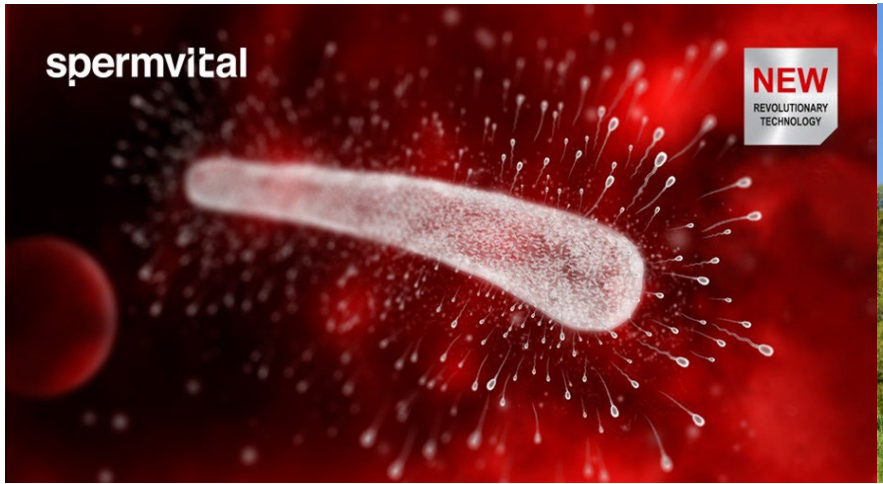
Treatment of chronic respiratory disease



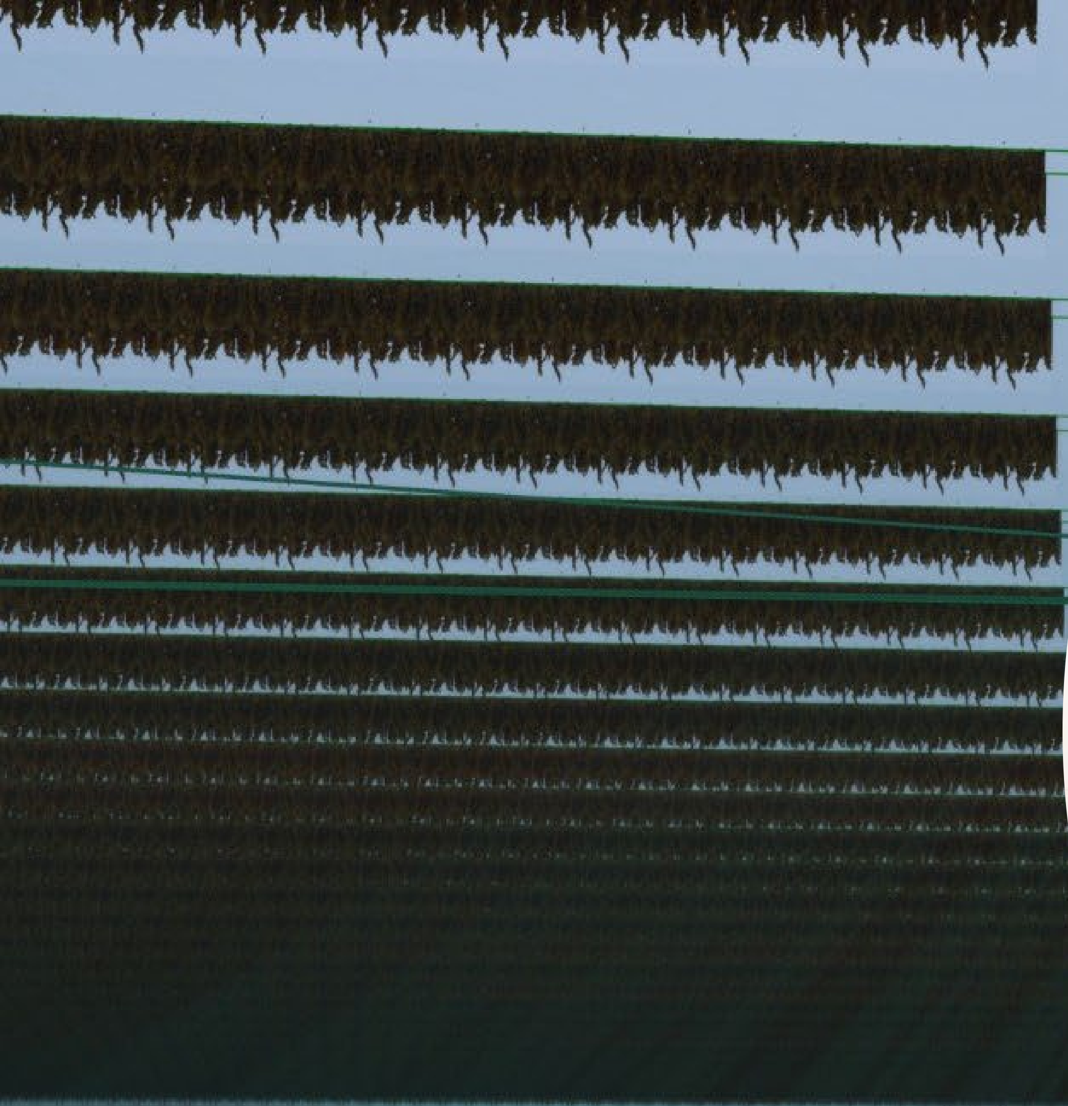


Alginate raft formed by Anti-reflux products

Slow release of sperm cells for artificial insemination



Gastric reflux/ heartburn medicine



SEAWEED INDUSTRY
-A part of the solution for a new bioeconomy in Norway

Thank you for your attention!

Foto: Olav Øiehaug