This review is prepared by Fine Food Íslandica ehf, a macroalgae cultivator and food producer. The review is based on the English version of The State and Future of Aquaculture in Iceland, with a sole focus on macroalgae cultivation.

Table of Content

I . General comments

The State and Future of Aquaculture in Iceland report outlines important considerations, benefits and social and environmental considerations of macroalgae cultivation. However, the status report and future recommendations include erroneous data, stakeholder engagement seems to have omitted important stakeholder groups, thus, the author of this review hopes to provide additional information and references to science research in hopes to fill in gaps on the current state and future potentials.

Seaweed cultivation at sea is an extractive activity which absorbs nitrogen and phosphorus from the marine environment, the same nutrients that phytoplanktons and natural seaweed forests require to grow. The impact of large-scale seaweed farms in marine environments without eutrophication problems have not been fully studied. Large farm installations need to thoroughly study nutrient availability, avoid shading light and disruption to diversity and the natural habitat.

Further research and assessment is needed to verify the viability and sustainability of several of the proposed development opportunities in the report, i.e. carbon capture/storage credits and integrated multi-trophic aquaculture (IMTA). These concepts have not reached commercialisation stage, neither in Europe nor globally. Sinking farmed seaweed as carbon storage on a commercial scale requires life-cycle analysis and still lacks scientific evidence for proof of viability (further explained in the carbon sequestration section below). IMTA requires intentional farm design based on scientific modeling of nutrient cycles and environmental conditions to achieve desired mitigative effects (further explained in the IMTA section in this document). A study at a commercial polyculture site in China has found a negative impact to important phytoplankton primary production due to reduction of ambient nutrient, light and water mixing by large scale kelp and shellfish aquaculture (Shi et al., 2011). It is essential that developmental and regulatory goals regarding these concepts be based on scientific methods and recommendations and to proceed with caution.

Biosecurity, traceability, disease and outbreak identification, prevention of transboundary contamination and maintaining genetic diversity in wild stocks are highlighted as significant challenges to seaweed cultivation sustainabilty in [a policy brief by UN University and the Scottish Association for Marine Science.]

II. Major environmental and social impact considerations

Here are several major considerations that need to be highlighted:

1/ Seaweed cultivation is an extractive activity. Large scale cultivation may compete with phytoplanktons and natural flora for nutrients and light. A thorough environmental impact assessment is essential before establishing large farm sites. Farm scale needs to work within ecological carrying capacity, e.g. nutrient availability and bottom benthic conditions to avoid negative impact to natural habitat, food web and other marine species.

2/ The state of seaweed cultivation is limited to a very few species. Monoculture and selective breeding pose multiple risks to the environment around the farm site e.g. disease, contamination and reduction in diversity. Hydrodynamics present conditions that make boundary establishment and containment of impact more difficult than land agriculture. Shedding and escaping of seed material into the marine environment is highly likely to occur with current seeding methods in seafarming.

3/ Scientific evidence is lacking in the quantification of carbon sequestration and storage. Sinking of farmed seaweed to deep sea has not reached proof of concept and is being debated in the scientific community which expresses concerns of the uncertainties (e.g. long-term storage is not proven, viability, very large areas of cultivation needed) and possible negative environmental impacts, e.g. over extraction of nutrients, smothering of deep sea benthic ecological communities and unintended deposits, etc. (more info and citations to follow on the carbon storage section below).

4/ IMTA effluent nutrient bio-remediation with seaweed cultivation needs to be better studied.

In an IMTA, bio-remediation species are placed into a system following quantifiable nutrient cycling principles and models. Coupled with varied environmental conditions in individual sites (current direction, dispersal speed, depth, etc.), and the soundness of farm design (system needs to be intentionally designed to address nutrient cycling and the timing of crop nutrient loading and absorption, etc.), the mitigating effects of seaweed aquaculture need site-specific, scientific research to quantify the degree of effectiveness in increasing sustainability in finfish farming (more details on IMTA follow).

5/ Mechanisms to safeguard the transfer of knowledge and benefits from seaweed cultivation to local communities are needed. Proportionality of rules and public research funding needs to enable both small and large scale developments.

6/ Effective monitoring and response systems are needed against invasive or foreign species, detection of disease, parasites and loss in diversity for wild stocks.

7/ Environmental and social baseline studies are urgently needed before development as bases to detect changes to the native ecological communities and social communities related to seaweed farming and production.

8/ Seaweed produced near fish cages may be contaminated by medicines, parasites, biofouling and undissolved waste from fish effluents. Food safety research and guidelines are needed.

III. Carbon sequestration and carbon credits

Carbon dioxide removal (CDR) technologies are swiftly gaining popularity although the quantification of effectiveness and environmental implications from large-scale application is very limited. Life Cycle Assessment is used to assess the impact and performance of CDR technologies throughout their life-cycle.

To achieve negative emissions to result in negative greenhouse gas (GHG) emissions, the CDR technology must 1/ permanently extract GHG; 2/ quantify all up and down stream emissions from its activities; 3/ the quantity of GHG removed must be greater than its emission. Side-effects to social and environmental conditions must be included into the quantification (Terlouw et al., 2021).

Ocean Rainforest, a leading seaweed cultivation company in Europe expressed that seaweed cultivation operations in Europe have not reached carbon neutrality due to carbon intensive production of farm anchoring systems, energy for transportation to perform farm activities and processing harvest (pers. Comm. with Olavur Gregersen, 2021).

Carbon fixation and sequestration differ in time scale of storage (Terlouw et al., 2021, Rose & Hemery, 2023). Carbon capture from farming macroalgae is often assumed as permanent sequestration despite the lack of consideration of the permanence of fixation—to include carbon accounting for the end product, entire product life cycle and its carbon composition. Monitoring of both carbon uptake and permanence are still needed to reliably assess macroalgae cultivation's carbon fixation benefits (Rose & Hemery, 2023).

Sinking farmed seaweed as carbon storage lacks scientific evidence
Scientific evidence and peer-reviewed protocols are lacking on the effectiveness in sinking large-scale farmed seaweed, impacts to carbon cycle and marine life. Research is lacking in environmental and social risk assessments from large scale farming and sinking:

1/ the ecological carrying capacity to support large extractive actives,
2/ impact to food webs, and
3/ deep-sea ecological communities from large-scale farming (Campbell *et al* 2019, National Academies of Sciences Engineering and Medicine 2021, Ricart et al 2022).

The quantity and timescale of carbon storage in the deep sea with such a method has not been scientifically quantified nor verified.

Based on current seaweed cultivation and sinking technology, 400,000km2 would be needed to grow enough macroalgae to 1 gigaton of carbon fixation, equaling 16.4 billion seaweed growing rafts of current design (Ross, Tarbuck, & Macreadie, 2022).

IV. Integrated Multi-Trophic Aquaculture (IMTA)

In an IMTA system, multiple extractive species (e.g. mussels, polychaetes and seaweed) are intentionally cultured with fed species (e.g. fish) to sequester organic and non-organic effluents and particulate organic matter from fed species. The design of the system needs to be based on quantified nutrient models and careful consideration of the environmental and biological factors of the site, with the goal to optimise nutrient recycling, thus, reducing nutrients released into the natural habitat (Edwards, 2015; Nderlof, Verdegem, Smaal & Jansen, 2022).

Despite proof of concept, the effectiveness of commercial scale IMTA is still uncertain and under investigation by scientific research. The bioremediation efficiency of commercial scale IMTA system has not been properly quantified and verified at commercial scale (Nderlof, Verdegem, Smaal & Jansen, 2021). Calculations in IMTA studies are mostly based on the reported maximum efficiencies in literature, thus overestimating nutrient retention (Nderlof, Verdegem, Smaal & Jansen, 2021).

Several biological and environmental factors affect the uptake of nutrients from fish cages, e.g. quick dispersal of waste by local and tidal currents; mismatch of the peak uptake season in kelp (spring) with the peak waste release from salmon (end of summer, occurring after the kelp are harvested); the extensive amount of seaweed and bivalve culture lines needed for effective and significant bioremediation of fish cages also pose operational and spatial challenges. (Nderlof, Verdegem, Smaal & Jansen, 2021).

Readers should be aware that nutrients and POM from finfish aquaculture will not be fully mitigated by IMTA. In a closed system, it is estimated to be 45-75% of nutrients mitigated and 40-50% for properly designed and implemented open systems adapted to local environmental factors (Nderlof, Verdegem, Smaal & Jansen, 2021).

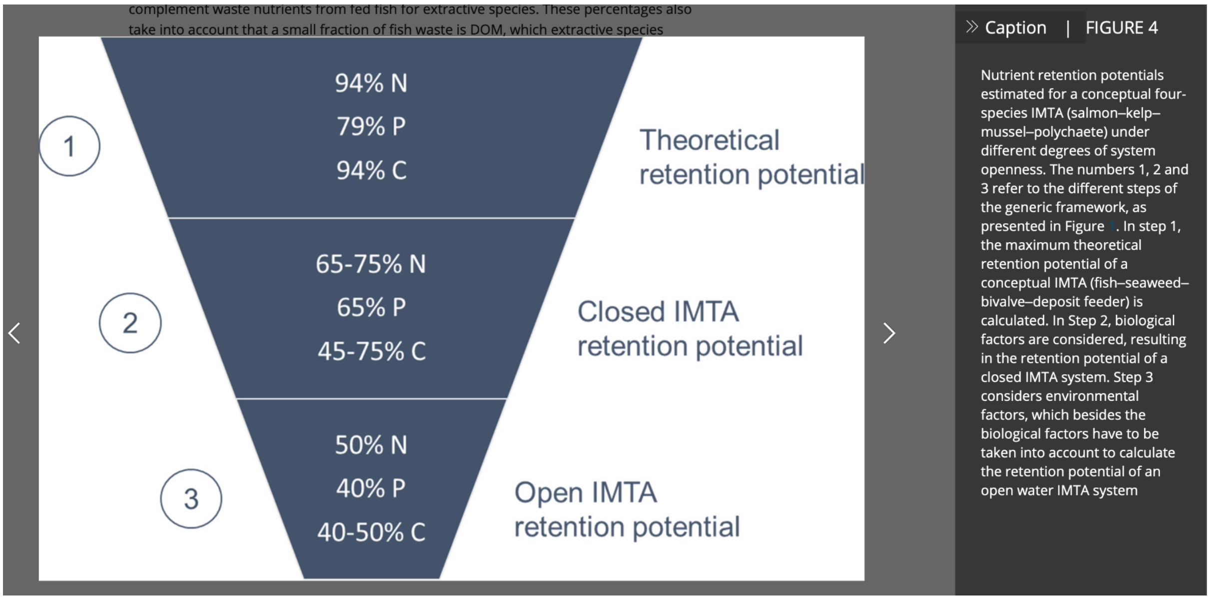

Figure from Nderlof, Verdegem, Smaal & Jansen, 2021.

Conflicting IMTA data states that the commercial uptake of IMTA in Europe is close to none (Edwards, 2015, Hughes & Black, 2016, Nderlof et al., 2022). Negative trade-offs for European aquaculture are cited as reasons for the low uptake of IMTA (Hughes & Black, 2016):
1/ availability of space,
2/ the inability of highly industrialised fish farming industry to adapt to increased complexity of cultivating multiple species and
3/ the low economic value of shellfish and seaweed as compared to fin fish lack financial incentives.

V. Sustainability in Icelandic seaweed cultivation

In light of rapid new seaweed aquaculture industry development, the impact of large-scale seaweed cultivation in non-eutrophic marine environments lacks comprehensive studies. Several environmental impacts detailed in scientific literature may have potential important implications for the sustainability of Iceland's environment and fisheries:

1. ocean ecosystems in both nearshore, offshore 1,2,3 and deep sea areas 1,2,3,4 are likely to be affected; reduction of phytoplankton primary production 1,2,3,5.
2. huge marine areas and amount of farming structures are required to make seaweed cultivation a viable Carbon Dioxide Removal (CDR) technology 1,2.
3. changes to hydrodynamics and marine traffic 1,2,3,5
4. genetic alteration to natural algal populations from monoculture and breeding technologies 1,2,3
5. potential breeding ground of algal diseases and invasive species 2,3,
6. entanglement of marine mega fauna 1,2,3, including protected species.

VI. Other important considerations to the development of the Icelandic seaweed industry:

i. Environmental and social baseline studies are urgently needed before planning large-scale developments.
ii. Seaweed industry has the potential to create diverse and high-tech jobs, but need mechanisms to ensure transfer of knowledge, opportunities and benefits to local communities for cooperative development beyond primary production level.
iii. Foster open communication, inclusivity and collaborations between scientific communities, regional and national governmental bodies, experienced cultivators, businesses and local communities.
iv. Delineate scale in licensing policy. Proportionality of rules and fees to the scale of development, ensure suitability for small scale farmers; provide support in testing and research costs to small ventures.
v. Maintain the reputation of sustainable Icelandic fisheries and avoid greenwashing.
vi. Effective monitoring and accountability.

VII. Comments on specific information in the report

The following pages are compiled in effort to strengthen the report and provide additional perspectives based on scientific research and references, as well as experiences from seaweed farming stakeholders in Iceland that were omitted in the report.

Section 7.1.1, P.215:

> "Today, larger scale commercial macroalgae operations have focused on wild harvesting, with limited macroalgae cultivation to date."

This only applies to Europe. "36 million tonnes (wet weight) of algae[3] were produced in 2020, of which 97 percent originated from aquaculture, mostly marine aquaculture." (FAO, 2022)

7.1.3 Figure 7.6

The producers listed in this figure are a mix of primary seaweed producers and processing companies (which buy from primary producers).
The figure left out seaweed aquaculture producer, Fine Foods Íslandica ehf, which has been cultivating *S. latissima* since 2017 and has developed and sold seaweed for food products since 2021. Glæðir, a seaweed fertiliser producer for decades, is also omitted.

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> Point 1. "There is a wild harvest cap… Although there is room for additional wild harvest, expansion beyond current limits will likely require aquaculture."

The harvest cap refers to Ascophyllum nodosum, however, at 12-17cm/year growth rate of the seaweed (at study sites in Eastern Canada), the cost of aquaculture production is at least 11,6 fold of wild harvesting, therefore, not deemed economically viable (FAO, 1987).
https://www.fao.org/3/X5819E/x5819e00.htm#Contents

It should note that due to slow growth rate, at maximum 1.9 μm per day (based on study in the Ria de Vigo, Portugal (Addey & Mckibben, 1970)), and estimated to be slower in more northern latitudes, **Lithothamnion cannot be considered a renewable resource.** Studies show that extraction of dead and live Lithothamnion both alter the structure of macrobenthic community and create irreversible damage to the maërl bed from sedimentation as a result of dredging during harvesting (Grave, Fzakerley, Kelly, Guiry et al., 2000).

Point 2. The report omits the fourth company experimenting with macroalgae cultivation. Fine Food Íslandica ehf runs the first hatchery in Iceland to produce seaweed from seedlings induced from local parental seaweed. In collaboration with Nesskel ehf, a mussel production company, the seedlings are deployed for out planting to seafarm growlines and harvested between April and September. The harvested seaweed is made into food products and has supported bioplastic research.

P.222

> "Eldey Aqua has worked with Arctic Fish, to cultivate sugar kelp (S. latissima) with salmon and Icelandic scallops in an integrated multi-trophic aquaculture (IMTA) system (more details on IMTA follow)."

The IMTA concept and example needs to be more clearly defined and be assessed by science research, in particular to the quantification of remediation of particulate organic matter and inorganic and organic nutrient cycling.

Food safety considerations need to be considered when seaweed is harvested from near aquaculture operations where medicine, parasites and biofouling agents are present.

P. 224

> 4. Algae can act as a low-carbon input in supply chains
> "Some projects have also experimented with integrating seaweed in livestock feed to reduce methane in cattle productions, with some results showing reductions of over 80%.382"

The research on 80% methane reduction is based on the application of the unique bio-chemical from an invasive seaweed that is non-native and not available in Iceland, therefore, a misleading example for this report.

This report did not analyse the risks and limitations of seaweed cultivation. Some possible major risks being:

- Over-extraction of nutrients and reduction of light for phytoplanktons and natural sea forests and impact to food chain by large scale farms
- impact to diversity and local marine ecological community structure due to monoculture and selective breeding from limited genetic material, especially in big scale farms
- Hazards to marine mammal migration passages or marine boat traffic by large scale farms or farms that are ill-positioned
- diseases and parasites in high density farms, and the potential spread to local natural population (Cottier-Cook et al., 2021).

P. 226

> "Some companies researching the cultivation of macroalgae, have collaborated with fish aquaculture to utilize ocean space389"

Per communication with Matvælastofnun, “the collection or cultivation of seaweed is considered to be a primary production of food within the meaning of the Food Act no. 93/1995” (pers. comm., 2021 and 2023). Farm lines cannot “be placed too close to fish farm installations or in places where there is frequent boat traffic.”

The acceptable distance to fish farms need to be more clearly delineated in regulation.

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Clear legislation is essential to development, however, based on my experiences in developing macroalgae cultivation in Iceland, I strongly disagree with this statement “Macroalgae cultivation is not yet legislated specifically which has halted research and development for commercial production.”

Research and development projects in preparation for commercial production have been awarded public funding (Tækniþróunarsjóður, Lóa, Uppbýggingasjóður) and multiple projects to support commercialisation are underway in the last few years. Various research and prep work are necessary prior to commercialisation and can be done despite licensing prospects.

Table 7.23

The key parameters described are not adapted to Iceland’s conditions and considerations contain erroneous information, e.g. seeded lines placement at 10-20m is not practiced by farmers (US, Faroe Islands and Iceland) as it will not provide good yield from very low light conditions.

According to grow manuals published by scientific research institutes and practicing farmers and personal experience, *S. latissima* in the North Atlantic will not tolerate above 13*C temperature for a prolonged period.

High light exposure is not recommended during grow out time during summer—bleaching of seaweed may occur while nutrients in Icelandic water is at lowest during summer.

Ocean habitats—important considerations need to include:

- Light shading
- Carrying capacity of location i.e. nutrient availability to support projected yield

- Marine mammal traffic and habitats—entanglement, especially with large farms that occupy an extensive area

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> “Macroalgae cultivation may benefit from being located close to wild harvest and fish aquaculture
> Integrated multi-trophic aquaculture (IMTA) systems could be established while considering necessary spacing between operations. For example, in the Faroe Islands, installations must keep 500m distance from the edge of fish aquaculture farms.409”

1/ The example of Faroe Islands is misleading. The seaweed cultivation in the Faroe Islands next to fish aquaculture is incidental, decided by logistical and business reasons (pers. comm. with Olavur Gregersen, 2021; Fletcher, 2019), not intended to be an IMTA system, nor with research to quantify the effects. This is, therefore, not a good example to assess or promote the suitability of IMTA.

2/ “Additionally, algae cultivation could use existing infrastructure such as processing and drying facilities from wild harvest in Breiðafjörður…”
The facilities in Reykhólar and Stykkishólmur are operating at full capacity or with very limited availability for contract work.

P. 233
Figure 7.10 omits macroalgae aquaculture in Reykhólahreppur and Strandir.

P.234
Offshore IMTA compatibility is still in infancy (Buck, Nevejan, Chambers & Chopin, 2017). Globally, all except for one offshore IMTA site are at experimental and pre-industrial stages (Buck, Troell, Krause, Angel et al., 2018).

7.4.1, p. 235
Processed algae for human food, bio-stimulant are also opportunities for value added products. Energy is one of the major costs of scaled up seaweed aquaculture production. Geothermal energy adds a great competitive advantage.

7.4.3
Conflicting IMTA data states that the commercial uptake of IMTA in Europe is close to none (Edwards, 2015, Hughes & Black, 2016, Nderlof et al., 2022). Negative trade-offs for European aquaculture are cited as reasons for the low uptake of IMTA (Hughes & Black, 2016):

1/ availability of space,
2/ the inability of highly industrialised fish farming industry to adapt to increased complexity of cultivating multiple species and
3/ the low economic value of shellfish and seaweed as compared to fin fish lack financial incentives.

Decreased primary production rates of phytoplankton in important polyculture sites in China is found due to reduction of ambient nutrient, light and water mixing by large scale kelp and shellfish aquaculture (Shi et al., 2011).

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Please refer to Carbon Sequestration section above.

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IX. Author background in seaweed research and cultivation:

2016-2018 Completed and graduated from University of Westfjords with a master degree, research in Coastal and Marine Management, thesis focused on the Local ecological knowledge on seaweed: A case study of the socio-ecological system in Reykhólar, Breiðafjörður

2017 Began research on seaweed cultivation and synergy with mussel farms in Iceland

2018-Current develop seaweed hatchery and cultivation techniques suited for Iceland in collaboration with mussel and coastal farmers. Seeding farm lines with zoospores from local seaweed induced in own hatchery

2021 Established Fine Foods Íslandica ehf, a company specialising in seaweed cultivation and food production, launched first seaweed food product

2021 Completed 5-week full-time trainee program at Ocean Rainforest in the Faroe Islands

2022 Launched 3 more seaweed products

2023 Additional pilot farm in Steingrímsfjörður and creation of seaweed farming educational course open to public in collaboration with coastal farmers (project in progress)