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Report

A new Norwegian bioeconomy based on cultivation and processing of seaweeds: Opportunities and R&D needs

A research work supported by Innovation Norway

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ABSTRACT
Cultivation of macroalgae at the lowest trophic level, using only sunlight and nutrients from the sea while taking up CO_2, will have a neutral carbon footprint and the biomass will contribute significantly to meet the demand for food, feed, materials, chemicals, fuels and pharmaceuticals in near future. Through a new bioeconomy based on cultivated macroalgae Norway will establish a future feedstock bypassing the competition with land-based agricultural resources and at the same time contribute to the replacement of fossil resources. This blue bioeconomy will strenghten Norway's role as the leading seafood nation as well as a leading supplier of marine, sustainable biomass. In order to boost a new bioeconomy based on cultivated macroalgae, three priority areas must be focused:

- Biomass production technology
- Biorefinery prosesses
- Marked and product development

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1 Preface

This research work was initiated by the Norwegian Ministry of Fisheries and Coastal Affairs and was financed by Innovation Norway. The working authors have received valuable contributions through discussions and inputs through a dialogue meeting held in Trondheim on the 21. November 2013, and further through discussions with international experts on a meeting in Copenhagen on the 16. January 2014 financed by the MacroPlatform project (NFR pr. Nr. 233872).

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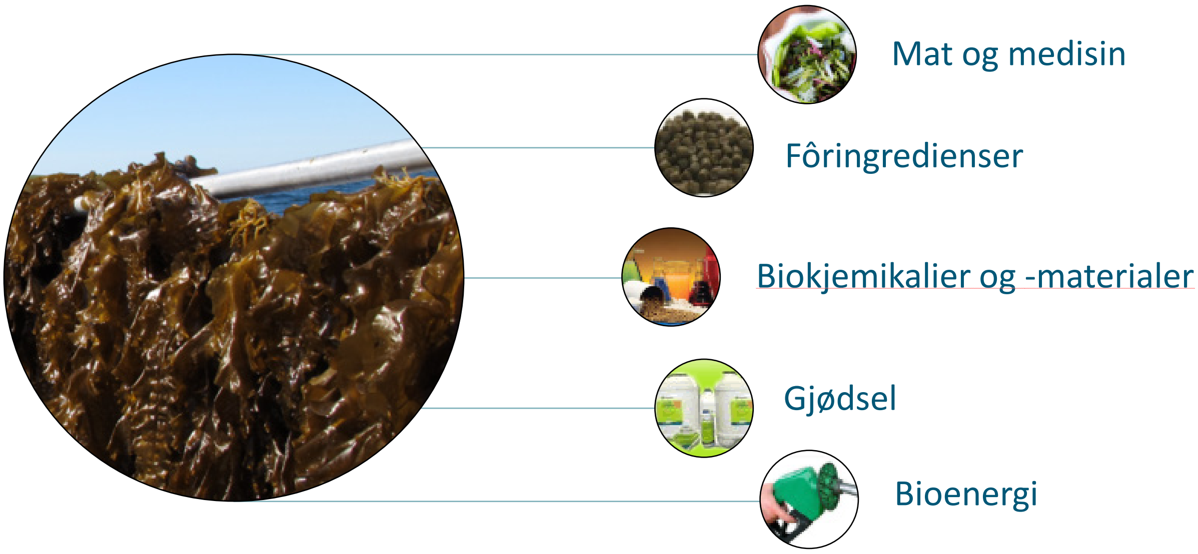
Figure 1.1 Cultivated sugar kelp (Photo: SINTEF Fisheries and Aquaculture).

2 Norsk sammendrag

Denne utredningen har tatt for seg muligheter og forskningsbehov knyttet til utviklingen av en ny norsk bioøkonomi basert på dyrking og prosessering av makroalger. Oppdraget ble initiert av Fiskeri- og kystdepartementet og SINTEF Fiskeri og Havbruk har utarbeidet prosjektrapporten med innspill fra diverse aktører. Prosjektrapporten har vært støttet av Innovasjon Norge gjennom Bioraffineringsprogrammet, som har som målsetning å styrke kunnskapsgrunnlaget, tverrsektoriell kompetanseflyt og bevisstgjøre bedrifter om ny teknologi og nye markedsmuligheter.

2.1 Dyrkede makroalger som råstoff

Interessen for miljøvennlig dyrking av makroalger som alternativ til landbasert råstoffproduksjon vokser raskt både nasjonalt og internasjonalt. Dyrkede makroalger kan utgjøre et nytt og viktig råstoff for fremskaffelse av verdifulle komponenter til anvendelse i mat- og helseprodukter, dyre- og fiskefôr og til produksjon av biokjemikalier og –materialer, gjødsel og 3. generasjons biodrivstoff (Figur 2.1). I Norge har vi 175 brune, 200 røde og 100 grønne arter av marine makroalger og dyrkingsmetoder finnes for flere av disse. Mulighetene for innovasjon og næringsutvikling basert på helhetlig utnyttelse av råstoffet som dyrkede makroalger representerer er enorme. Utvikling av teknologi for kostnadseffektiv dyrking og helhetlig utnyttelse av råstoffet i nye prosess- og produktlinjer er nødvendig for å fremme en ny biomarin økonomi i Norge.



Figur 2.1. Makroalger, som for eksempel sukkertare, kan dyrkes opp og brukes som råstoff for produksjon av en rekke viktige produkter.

Norge har lang kystlinje med god vannkvalitet, lang tradisjon for å høste av havet og er internasjonalt ledende innen marine operasjoner og lakseoppdrett. Forutsetningene for å industrialisere makroalgedyrking er derfor er meget gode. For å lykkes er det viktig å utvikle ny teknologi for å etablere en stabil og forutsigbar biologisk produksjon av noen få enkeltarter, og det er tilsvarende like viktig å utvikle og kommersialisere nye produkter fra disse artene for å sikre lønnsom produksjon og bygge en industri med gode framtidsutsikter. I Tabell 2.1 er produkter og markeder for en makroalgebasert bioøkonomi presentert.

Table 2.1: Mulige produkter fra tang og tare-arter som kan dyrkes i Norge, og antatt prisleie.

Komponent	Potensielt produkt og/eller marked	Potensielt prisleie*
Hele planter	Mat	Lav-medium
Ekstrakter	Kosmetikk	Medium
Karbohydrater / polysakkarider	Fortykningsmidler, viskositetsøkende midler	Medium
Polysakkarider	Prebiotika	Medium
	Farmasøytiske produkter	Høy
	Substrat for fermentering (biodrivstoff, fôrprotein)	Lav
Protein / aminosyrer	Fiske- og dyrefôr	Lav-medium
	Bioaktive peptider (fôr og mat)	Høy
Polyfenoler	Antioxydanter (mat, fôr, kosmetikk)	Høy
	Antimikrobielle produkter (mat preservering, anti-begroing m.fl.)	Medium-høy
Aske	Gjødsel	Lav-medium
	Verdifulle mineraler	Medium-høy

*: Lav: < 10 kr/kg; Medium: 10-100 kr/kg; Høy: >100 kr/kg

2.2 Anbefalinger

For å sikre en lønnsom utvikling av den nye bioøkonomien, basert på dyrking og prosessering av tang og tare, anbefales det å prioritere følgende forskningstemaer:

- Utvikling av protokoller for oppstart og dyrking av et fåtall arter under norske forhold
- Utvikling av dyrkingsteknologi for industriell produksjon i sjø
- Utvikling av prosessteknologi for helhetlig utnyttelse av råstoffet i bioraffineri
- Utvikling av nye volum- og høyverdiprodukter for kommersialisering
- Kartlegging av potensielle miljøinteraksjoner som følge av taredyrking

Forskningstemaene vil danne grunnlaget for utvikling og etablering av en kunnskapsplattform for industri og forvaltning.

Parallelt til utvikling av ny dyrkingsteknologi er det viktig å identifisere høyverdiprodukter som kan bidra til et lønnsomt bioraffineri, og å identifisere optimale kombinasjoner av høy-volum/lav-pris og lav-volum/høy-pris produkter tilpasset årstidsvariasjoner og høstetidspunkt. Videre må det utvikles kostnads-, ressurs- og energieffektiv prosessteknologi som kan integreres i et helhetlig bioraffinerikonsept, der alle komponenter fra biomassen utnyttes. Analyser og forståelse av nasjonale og globale markedsmekanismer og markedspotensialer for nye makroalgeprodukter er avgjørende for å utvikle en konkurransedyktig verdikjede.

Det er viktig å få på plass grunnleggende kunnskap om både biologiske premisser og teknologiske muligheter, samt ha et realistisk forhold til hvor raskt en ny næring vil begynne å tjene penger på produkter og bli selvgående. Myndighetenes rolle vil være å sikre finansiering av forskning og innovasjon gjennom langsiktige programmer, og at det fokuseres på spesialisering hos sterke forskningsmiljøer.

Dyrking av makroalger skiller seg fra fiskeoppdrett ved at det ikke tilføres fôr, og lovverket for disse to ulike aktivitetene må derfor spesifiseres. Integrert akvakultur (IMTA) er attraktivt for

Norge med alle sine lakseoppdrettsanlegg og det er viktig med et lovverk basert på ny kunnskap om algedyrking til sjøs slik at denne muligheten ivaretas på en god måte.

Makroalger trenger sollys og må derfor dyrkes i de øverste vannlagene (0-15 m) i sjøen. Dette medfører at det trengs store sjøarealer til industriell dyrking, og her vil myndighetenes rolle være å tilrettelegge for at arealer blir gjort tilgjengelige for dyrking. Det anbefales at det åpnes for tildeling av tidsbegrensede konsesjoner for prøvedyrking, slik at gode dyrkingslokaliteter kan identifiseres og miljøinteraksjoner kartlegges før valg av endelige lokaliteter foretas.

Figur 2.2 Algeas tareanlegg på Nordmøre våren 2014 (Foto: SINTEF Fiskeri og havbruk AS).

3 Introduction

3.1 Trends in the bioeconomy

Overall trends (international/national) points towards products that can be linked to renewable biomass, reduced emissions, closed cycles and complete utilization of the feedstock. A transition is needed towards an optimal and renewable use of biological resources and towards sustainable primary production and processing systems. These systems will need to produce more food, fibre and other bio-based products with minimised input, environmental impact and greenhouse gas emissions, and with enhanced ecosystems services, zero waste and adequate societal value (Fig.3.1).

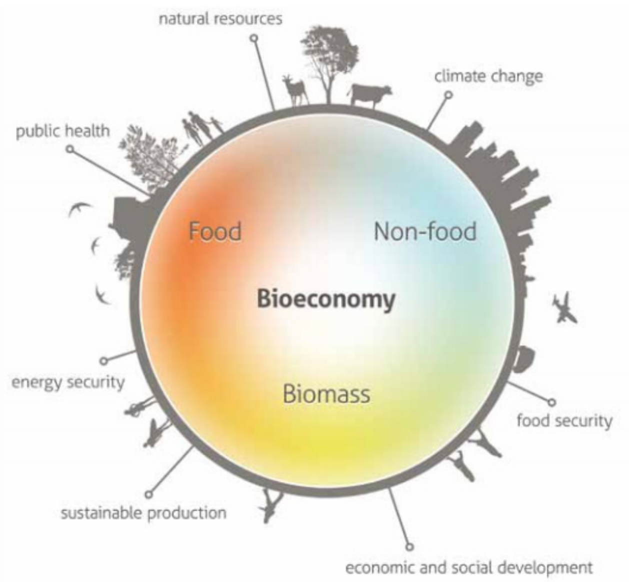


Figure 3.1. The European bioeconomy, also including the great global challenges (illustration from www.becoteps.org).

The transition from fossil-based industries towards low carbon, resource efficient and sustainable production is a major challenge. It entails the transformation of conventional industrial processes into environmentally friendly, integrated bio-refineries and new bio-based products. Research and innovation will provide the means to reduce the European Union's dependency on fossil resources and contribute to meeting its energy and climate change policy targets for 2020.

The integrated bioeconomy we envisage is not simply about science, but is rather an integration of science with business and society. In the EU, it is already worth more than 2 trillion € annually and employs over 21.5 million people, predominantly in rural areas and often in SMEs (http://www.plantetp.org). One of the Grand Societal Challenges in EU is: *Food security, sustainable agriculture, marine and maritime research and the bio-economy,* which is one of the priorities of the Europe 2020 strategy. According to the Roadmap to a Resource Efficient Europe (2011) the Commission will "Address the indirect land use change resulting notably from the renewable energy policy (continuous)", "Support the sustainable use of marine resources, and identify innovative business opportunities in the maritime and coastal economy (Communication on "Blue Growth", 2012)" and "Ensure sustainable use of algae for biofuels".

All the above statements support a further development of a whole integrated macroalgae industry in Norway, and also that Norway might have an obligation to develop a new sustainable biobased industry based on production, harvesting and processing of macroalgae. In this development the industry is a major stakeholder, aiming for high and predictable biomass production and quality, and high and predictable prices of the products derived from it (Fig. 3.2). The ecosystem is another "*stakeholder*" in the macroalgae industry as the biomass production will interact with the environment and set footprints. Third, the regulatory authorities aim for a sustainable utilization of the natural resources through the management of sea areas to allocate space for cultivation. A knowledge-based interrelation between these three sectors is a prerequisite for a successful development of the macroalgae industry.

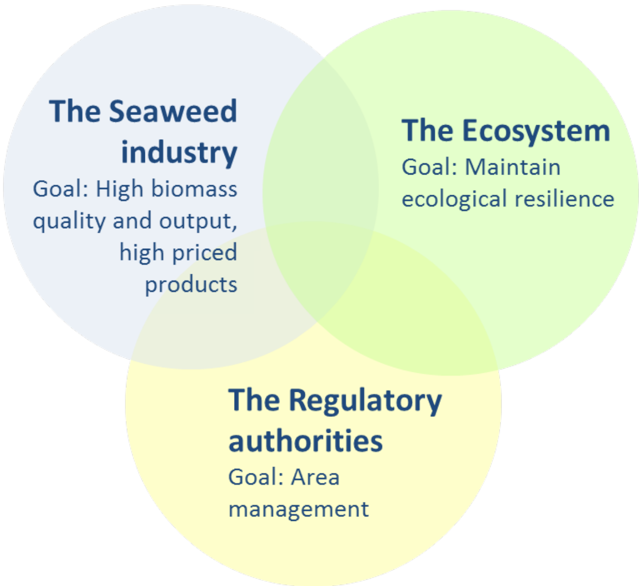


Figure 3.2. The three sectors interrelated in the seaweed based bioeconomy.

3.2 The rationale for a Norwegian bioeconomy based on cultivation and biorefining of seaweeds

In 2050 we will need 70% more food than today. The sea counts for 50% of the total biomass production and the terrestrial for the other 50%. However, only 2% (on energy basis) of the food comes from the sea (aquaculture and fisheries) directly. These facts have to be taken into consideration in the development of the bio-based economy and reflected in research, technological development, innovation, industrialisation and market and framework development. The substantial resources of nutritious oceanic water, the rapid and effective biomass production of seaweeds at low temperatures and the gravitational advantages of producing biomass in the oceans should thus be explored and exploited fully for renewable biomass production. Seaweeds are one of the largest un-exploited global biomass resource and Norway has many clear opportunities for seaweed cultivation and processing, such as a long coast with high-productive areas and strong competence within aquaculture, off-shore constructions and seaweed biotechnology. For Norway cultivated seaweed biomass is a new entry into the growing global bioeconomy, which according to The World Economic Forum will have a market value of 300 billion $ by 2020.

In Norway the research on macroalgae cultivation has been sporadic for several decades, but from 2008 the number of research projects and participants has increased. The main driver for this interest has been the potential for production of large volumes of a renewable biomass that is rich in carbohydrate and thus attractive for 3rd generation biofuel production. But seaweed biomass has potentials for multiple applications and can supply the global market with food, feed ingredients, pharmaceuticals and fertilizers, in addition to products that can replace petroleum-based materials. A biorefinery concept for cultivated seaweed biomass that approaches a complete exploitation of all the components in the raw material and that creates added value will be ultimate to succeed in the global market. *Still, a market pull for products made from macroalgae biomass is decisive for development of a bioeconomy based on cultivation and biorefinery of macroalgae.*

"The bioeconomy encompasses the sustainable production of renewable biological resources and their conversion into food, feed, bio-based products and energy"

(European Commission, "Innovating for sustainable growth: A bioeconomy for Europe", 13 February 2012).

3.3 Seaweeds as a feedstock for the bioeconomy

Cultivated macroalgae is considered one of the largest un-exploited global biomass resources for a sustainable production of food and replacement of fossil resources. While macroalgae traditionally have been cultivated at large scale for food and other purposes in Asian countries (Murata and Nakazoe, 2001; Nisizawa et al., 1987), the interest in European countries has been low. As a result Asian countries account for 99% of the global seaweed production, which was 16 mill tons in 2011 (FAO 2013). In Asia 99.9% of the utilized seaweed biomass is cultivated, whereas in Europe only 0.1% is cultivated. However, new trends and opportunities for multiple uses such as food and bioactive components of functional foods and feed-ingredients, phycocolloid production, fertilizers and biofuels, in addition to bioremediation services (Bixler and Porse, 2011; Buschmann et al., 2008; Fleurence et al., 2012; Gómez-Ordóñes et al., 2010; Holdt and Kraan, 2011; Kraan, 2010; Troell et al., 2009) have increased the interest of industrializing the cultivation of macroalgae also in Europe.

The value chain is not complete and pioneer companies have to climb many hurdles, both related to technology, biology and governmental administration as well as market development and financing. Several Norwegian companies are now about to start commercial cultivation in 2014, and licenses are currently the first milestone to be achieved. The time is now right to focus also on the processing of cultivated macroalgae through engagement by the existing bioeconomy industry and by initialization of new companies that want to receive cultivated biomass and produce diverse valuable products for different markets.

The first Norwegian companies with licenses for cultivation of macroalgae:

- Algea deploys their first lines with sugar kelp in February 2014 outside Kristiansund for production of biomass aimed for processing in their own factory.
- Hortimare Norway cultivates kelp in proximity to salmon farms for nutrients recycling in partnership with the salmon farmer Salmon Group in Solund in Sogn og Fjordane.
- Ocean Forest starts cultivation of kelp, among other species, in multi trophic aquaculture in partnership with Bellona and the salmon farmer Lerøy Seafood in Rogaland.
- Seaweed Energy Solutions has their cultivation areas for kelp outside Frøya and aims for industrial scale kelp biomass cultivation for use in biofuel and feed production.
- Val Videregående Skole in Nærøy will use their license for seaweed cultivation in education and research.

4 Cultivation of seaweed in Norway

4.1 Why cultivation?

Meeting the demand for food and energy from a global population growth of 2 billion people, reaching 9 billion before 2050, will require millions of tons of new biomass resources. Macroalgae belong at the lowest trophic level, use only sunlight as energy and extract nutrients from the sea while incorporating CO_2 into biomass. With one of Europe's largest economic zones and the length of the coastline reaching 2.5 times around equator, Norway has large suitable areas and a great potential for cultivation of macroalgae at an industrial scale.

4.1.1 The large kelps

Compared to East-Asia the seaweed cultivation in Europe is still in the developmental phase and comprise few species. Macroalgae like the kelps belong to the fastest growing plants of the world, produce large amounts of biomass and are cultivated without the use of fresh water, farmlands, fertilizers and pesticides needed for land-based cultivation. These large size brown algae prefer the growth conditions of the cold-temperate and arctic zones, which in Europe stretch from northern Portugal to northern Norway. This makes them attractive as future biomass producers for diverse industrial applications.

The first trials on farming of species of the Laminariales in the sea were undertaken for some years in the 1990’s in France and Germany, followed by Ireland and UK after 2000. At present kelp sea farming is also carried out in Denmark, Spain, Portugal, Færøyane and Norway. The systems currently most used for open-sea kelp cultivation in Europe are different concepts of rope cultures on long lines (Kraan and Guiry, 2001), deployed either vertically or horizontally in the sea (Fig.4.1). Ring systems (Buck and Buchholz, 2004) and textiles are also tested, the latter in combination with special carriers (Seaweed Energy Solutions). The ongoing EU-financed At~Sea project has demonstrated high biomass productivity on textiles.

The sugar kelp, "sukkertare", *Saccharina latissima* is one of the fastest-growing among the European kelp species and has the highest carbohydrate content. This species resembles Japanese kelp *S. japonica*, of which 4 mill tons wet weight are cultivated annually in China, Korea and Japan for use as food (kombu) and production of chemicals. Cultivation experiments with *S. latissima* in the North Atlantic coastal areas predict biomass production potentials of up to 340 tons wet weight per ha, however more conservative numbers range from 170-220 tons (Peteiro and Freire, 2009; Sanderson et al., 2012; Broch et al., 2013; Handå et al., 2013). Indeed, there is still a large variation in the biomass production observed in cultivation trials and precautions should be taken in extrapolation from small scale trials to industrial scale. In the nature *S. latissima* grow down to 30 m depth and resist wave heights corresponding to storm conditions. Cultivation should, however, preferably be done only in the upper 10 m. Strong water current means higher nutrients supply per time and potential for higher biomass production. Recent work has demonstrated that *S. latissima* has higher biomass per individual when cultivated in strong water current compared to sheltered sites (Peteiro and Freire, 2013; Skjermo et al.,2013).

Figure 4.1 Cultivation of sugar kelp on ropes (Photo: SINTEF Fisheries and Aquaculture).

The winged kelp, "butare", *Alaria esculenta* is also among the high biomass producers (Druehl et al., 1988) and has been cultivated in Ireland for the last 10 years. Kraan and Guiry (2001) have reported a production from 5-14 kg up to 45 kg wet weight per m rope, the latter equivalent to up to 450 tons ha^{-1}. *A. esculenta* grow naturally down to at least 8 m at moderately to highly exposed areas. The dry biomass weight of *S. latissima* and *A. esculenta* is reported to vary from 8-20% and the content of the storage carbohydrates mannitol and laminaran varies between 8-19% and 2-34% of the dry matter, respectively (Black, 1950; Haug and Jensen, 1954).

To meet the ecological differences and thus benefits along the long Norwegian coast and exploit the species diversity, several species should be considered for potential cultivation. Another Laminariales species interesting for cultivation in Norway is the finger kelp "fingertare" *Laminaria digitata*, which resembles *S. latissima* both in biology, composition and cultivation technology.

4.1.2 The smaller species

Interesting species are also found among the smaller, more fragile species from the red and green algae. However, some of these require tank cultivation during the whole life cycle and thus partly fail to exploit the environmental and geographic benefits obtained by sea cultivation. Cultivation protocols exist for several of the currently most interesting red species, like "søl" (*Palmaria sp*) and "fjærehinne" or Nori (*Porphyra sp*), and the green species "havsalat" (*Ulva lactuca*), and can be adjusted to Norwegian circumstances. The individual plants are small but they may have a high biomass production and contain valuable components that make them highly interesting for industrial applications. Because they are easy to collect in the littoral zone many species have a long tradition as food in the North-West of Europe. The average annual productivity of commercially relevant red algae has been reported to be in the range 33-113 tons s dry weight per ha (Gao and McKinley 1994). So far the interest for commercial farming of small brown, red and green macroalgae has been low in Norway. The reason could be insufficient knowledge about the species and potential applications. However, ongoing research aims to change this and collaboration with Irish, Scottish and Danish competence may facilitate the introduction of these species in Norwegian aquaculture. Thus, it is encouraging that at least one Norwegian company has now been awarded a license for cultivation of red species.

4.2 Cultivation strategies

Different species and applications calls for different cultivation strategies. Exploitation of both the biological potential of the species for production of an attractive biomass and the environmental conditions for optimizing of the growth rate and chemical composition can be obtained by adjusted technological solutions.

4.2.1 Seedlings production of kelp

Seedlings for on-growing in the sea can be produced from spores extracted from the sporangial areas (sorus portions) of wild, fertile plants and settled onto appropriate substrates (ropes or nets) for development and growth to juvenile sporophytes (Fig. 4.2). The spore formation is temperature sensitive and wild, European species normally develop sorus portions during the winter months. The developmental sequence from rope-seeded spores via gametophytes to juvenile, 3-5 mm long sporophytes ready for transfer to the sea takes two months and is currently a bottle-neck for mass cultivation of seaweed biomass. One strategy for eliminating this bottle-neck is to develop a scheme for year-round production of sorus portions on the kelp blade (Lüning 1988; 2005). A protocol for seedlings production of *S. latissima* has recently been adjusted and demonstrated to work well in Norway (Forbord et al., 2012). An alternative method is seeding by fragments from mass cultures of filamentous gametophytes (e.g. Zhang et al., 2008; Xu et al., 2009). Such cultures can be kept continuous for long periods and allows for cultivation of large numbers of gametophytes for seeding of lines or other growth substrates. Good protocols to avoid contamination and secure optimum viability are prerequisites for using this strategy.

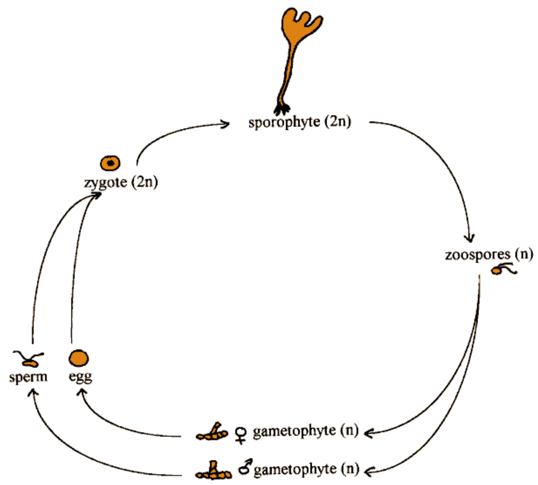


Figure 4.2. The life cycle of kelps like e.g. sugar kelp *S. latissima* and winged kelp *A. esculenta*. Seedlings are produced from the zoospores or the gametophytes. Both life stages attach firmly to growth substrates like ropes and nets and develop thereafter into large sporophytes ready for harvesting within 4-9 months.

4.2.2 Optimizing of chemical composition

The seasonal variation in chemical composition is characteristic for seaweeds. In general seawater has the highest nutrients concentrations during the dark season and gets depleted of nutrients during the microalgae blooms in the spring. Thus, the seaweeds have developed strategies to fit the seasonal changes in light and nutrients availability. The accumulation of carbohydrates typical for the Laminarales during the summer has been shown to depend mainly on the day length, as found for *L. hyperborea* cultivated in the laboratory in a seasonally changing day-length regime at constant high nutrient levels (Schaffelke, 1995). Nevertheless, nutrient enrichment during summer light conditions has been shown to reduce the content of soluble carbohydrates in *S. latissima* (Gordillo et al., 2006) by approximately 50%. In the same study the protein content in several *Fucus* and *Laminaria* species increased. However, in the integrated multi-trophic aquaculture (IMTA) study by Wang et al. (2014) increased nitrogen supply from a fish farm did not induce accumulation of nitrogen in the *S. latissima*, indicating that the kelps were nitrogen limited during the production phase. Manipulation of the chemical composition in one or another direction is thus complicated, and a thorough understanding of the seaweed ecophysiology is crucial for development of cultivation strategies that ensure predictable yield, composition and quality of the biomass.

4.2.3 Opportunities for IMTA

In temperate marine ecosystems, inorganic nutrients are abundant mainly during winter and early spring, before the phytoplankton depletes the nutrients in the surface layer from late spring leading to nutrient limitation all through the summer period (Paasche and Erga, 1988; Frette et al., 2004). However, in areas with intensive fish farming, inorganic nutrients may become available in higher amounts as a result of an increased nutrient emission rate from fish farms during the warm season (Mente et al., 2006; Wang et al., 2013).

Norway is the leading country for aquaculture production of salmonic species worldwide (mainly Atlantic salmon *Salmo salar*; FAO 2012). The aquaculture industry in Norway produced in total 1.31 mill ton salmon and rainbow trout in 2012 (Norwegian Directorate of Fisheries, 2013) with a use of 1.56 mill ton fish feed. Mass-balance models indicate that 45% of the nitrogen released from the salmon industry to Norwegian coastal waters, totaling about 50 000 t N yr^{-1}, is released as dissolved inorganic nitrogen (DIN) (Wang et al. 2013). Thus aquaculture is one of the largest sources of DIN effluents to Norwegian coastal waters Skarbovik et al., 2012).

Ammonium-N, which is the principal excretory product from protein metabolism in fish, can represent a significant nitrogen source for macroalgae in close proximity to fish cages at this time of the year if ambient nitrate concentrations are low (Ahn et al., 1998; Sanderson et al., 2008). Cultivation of macroalgae close to the fish farms may utilize these effluents for biomass production and contribute to a better exploitation of the fish feed. The concept is termed integrated multi trophic aquaculture (IMTA) (Chopin et al., 2004) and several studies report enhanced seaweed growth in IMTA with salmon (Abreu et al., 2009, Sanderson et al., 2012; Handå et al., 2013; Wang et al., 2014). Nevertheless, holding the rapid growth of e.g. *S. latissima* in spring and early summer together with the typical increase in fish biomass and feed use in late summer and early autumn suggested a seasonal mismatch between the maximum effluents from the fish farm and peak nutrient uptake in *S. latissima*. Accordingly, the potential of performing bioremediation services with direct recycling of the anthropogenic nutrient input from salmon farming by macroalgae should be considered taking the differing seasonal growth patterns of the species into account (Broch et al., 2013).

Norwegian salmon industry

Salmon and rainbow trout production	1.31 mill tons (2012)
Fish feed use	1.56 mill tons (2012)
Dissolved inorganic nitrogen (DIN) available for algae	45% (N-discharge from fish)

A: Estimated space requirements

Salmon production (5 000 tons):	30 ha
Seaweed production (5 000 tons):	30 ha

B: Biomass production over a two year period

Salmon	One production cycle	5 000 tons ww
		1 800 tons dw (36% dry matter content)
Seaweed	Two production cycles	10 000 tons ww (2 x 5 000)
		1 500 tons dw (15% dry matter content)

C: Bioremediation (IMTA)

A 5 000 tons seaweed farm (30 ha) will have a net uptake of 10% of the DIN per year from a 5 000 tons salmon production (30 ha).

(Wang et al., 2012; Broch et al., 2013; Handå et al., 2013; Wang et al., 2014)

4.2.4 Domestication

In cultivation of biomass it is a prerequisite that the plant holds a set of properties that makes the production and utilization economic feasible. Fast growth, large individuals, low loss, high resistance against diseases and epiphytic fouling, together with a high content of carbohydrates or proteins are the favoured properties for seaweed species aimed for biofuel or feed production. For extraction of high value components the requirements to large biomass productivity is less whereas the stability and predictability of the chemical composition is crucial. To obtain seaweeds with optimum qualities regarding these criteria breeding has been shown to be effective in China (Li et al., 2008) and Chile (Westermeier et al., 2010). In Norway it is not allowed to deploy hybridized or bred strains in the sea due to a risk for genetic interaction between domesticated strains and wild populations. The production thus has to be carried out using only region specific, natural strains.

4.3 Environmental interactions of seaweed farming

4.3.1 Effects on the pelagic ecosystem

Farmed seaweed will take up and utilize nutrient resources from surface waters (0-15 m) and by this affect the chemical and ecological state of open waters. Changes in state may become expressed as reduced concentrations of total nutrients and changes in structure and function of planktonic ecosystems, the main concern of European environmental legislation that are becoming implemented in Norway (The Water Framework Directive, WFD). As seaweed will tend to reduce nutrients and plankton biomass, large scale farming will have a potential to reduce other marine productivity. This effect is the opposite of for example the effect of fish farming, and most other human activities, which cause a release of nutrients to the environment. In both cases the potential environmental effect must be evaluated based on the changes in nutrients flows and productivity caused by the seaweed farm relative to the natural background state. Part of the assessment needs to be a potential cancellation of negative environmental effects.

4.3.2 Effects on the benthic ecosystem

Farmed seaweed will produce organic wastes which will be spread downstream of the farm and become degraded on the seafloor, with the potential of affecting the state of the benthic ecosystem. The production of organic wastes from natural seaweed forests is very high (Krumhansl, 2012). These plants lose their entire blades through natural seasonal processes, whereas farmed seaweed will be harvested. It is nevertheless important to quantify losses of degrading tissues from farmed seaweed and to assess the further ecological fate and influence of these wastes on the state of the benthic ecosystem. Small plants that have been outcompeted and other detached material from the farm/plant may also sink and affect bottom areas, giving increased nutrition for herbivore and detritivore animals and improve feeding grounds for fish (Vetter, 2005;2006), but also act negatively if deposition of such organic load results in de-oxygenation of sediments. The overall effect that farming of seaweed will have on surrounding water and seafloor ecosystems depends on the production scale of the seaweed farm, the biological state and carrying capacity of the ambient seawater, hydrodynamics of the location, and the depth and bathometry of the location. The changes in chemical and ecological state of pelagic and benthic ecosystems must be determined based on the common indicators used for such environmental assessments (Ferreira et al., 2011).

4.3.3 A new habitat

The seaweed cultivation farm will act as a new habitat, similar to artificial reefs, and as the seaweed grow, the habitat will increase in size and structural complexity. This artificial temporary habitat will develop during spring and summer, simultaneously with an increase in fauna activity and spawning periods for both invertebrates and fish. Fauna associated to kelp forests and other seaweeds are dominated by mobile animals with high dispersal abilities (Jørgensen et al., 2003; Waage-Nielsen et al., 2003; Christie and Kraufvelin 2004). These animals may to some extent colonize the plants and develop a fauna community within the cultivated kelps and increase biomass and possibilities for feeding areas for fish. This seaweed farm represents a new habitat as long as the seaweed grow, however bio-fouling also causes substantial problems for the farmer as the blades get so covered that they start to deteriorate. The biomass is thus normally harvested at early summer, implicating a drastic removal of the habitat. The effects of such intermediate habitats have not been evaluated.

Figure 4.3. A juvenile lumpfish living in a sugar kelp farm (Photo: SINTEF Fisheries and Aquaculture).

4.4 Potentials and opportunities for a seaweed cultivation industry

Based on Chapter 4.1 to 4.5 the most important potentials and opportunities for the development of a seaweed cultivation industry that forms the ultimate basis for a seaweed bioeconomy in Norway can be summarized as presented in Table 4.1.

Table 4.1. The most important potentials in seaweed cultivation and the opportunities this represents for industry development by Norwegian companies.

Potentials	Opportunities for seaweed farmers
Cultivation of 3-5 seaweed species	Cultivation protocols already exists for several species and can be adjusted to Norwegian conditions and scaled up
Large biomass supply	Large biomass production as a feed stock for industrial processing and extraction of valuable components
Valuable biomass	Complete exploitation in a bio-refinery for bulk and high value products
Low trophic level	Sustainable, non-fed biomass production (only sunlight and CO_2 as energy and carbon source)
Species diversification	High number of species with seasonal dependent characteristics that can be cultivated and exploited for extraction of valuable components
Strain improvement	Strains of high quality regarding biomass production, disease resistance and chemical composition can be targeted with breeding programs (currently not allowed by the Norwegian legislations)
Large cultivation areas	Cultivation areas with different qualities regarding nutrients, temperature and light can be exploited for diverse species
IMTA	Cultivation close to salmon farms optimizes the utilization of area regulated for aquaculture, improves the biomass production, approaches a closed N-cycle and may have beneficial environmental effects
Positive environmental interactions	Seaweed cultivation farms may function as new habitats for many organisms, also fish juveniles of economic value
Cultivation in artificial reef	Artificial reefs in the photic zone can be used for biomass production of selected seaweed species
Co-use of offshore structures	Seaweed cultivation within off-shore windmill parks optimizes the utilization of area regulated for energy production purposes
Use of existing bio-industry facilities	Biomass can be cultivated close to marine bio-industry localities along the coast for effective logistics

4.5 Challenges and limitations

An industry based on processing of cultivated macroalgae demands a stable and predictable delivery of biomass with defined qualities. The cultivation biology and technology must be developed to guarantee this. The challenges and limitations that need solutions obtained through basic and applied research are discussed below.

4.5.1 Area conflicts

The criteria for a good seaweed locality are so far not defined but according to the many cultivation trials and to commercial cultivation activities the requirements are not very restricted for kelps like *S. latissima*, *L. digitata* and *A. esculenta*. There is a need for description of the critical values and limits for good and predictable production, for use in mapping of potential cultivation areas. There is also a need for guidelines for evaluation of consequences of industrial scale macroalgal farming that comply with the Norwegian regulations.

Conflicts with alternative area use will probably be a reality despite that the Norwegian coastal line is among the world's longest. Today 800 km^2 is utilized for fish farming. According to the prognosis by Olafsen et al. (2012) 4 mill tons of macroalgae biomass will be cultivated in 2030. Using sugar kelp or other kelp species with resembling productivity and a conservative number for the biomass production (170 tons wet weight per ha) as example an area of about 2 500 km^2 will be needed for this. A 20 mill tons production in 2050 will require about 12 000 km^2. The question is whether the aquaculture industry will have access to such large areas in the future. Off shore cultivation may contribute to release the pressure on the near coastal areas whereas IMTA and seaweed cultivation for bioremediation may ease the access to inner coastal areas and fjords not suitable for fish farming (e.g. the national "salmon fjords"). However, long term dialogue with all stakeholders is important for the development of an industrial scaled production of seaweed biomass.

4.5.2 Cultivation technology

Application of seaweeds as a raw material for production of proteins and biofuels requires availability of very large quantities of seaweed biomass. A prerequisite for large biomass cultivation at sea is the on-land production of sufficient amount of high quality propagules or seedlings on substrates to be placed at suitable sites in the sea for on-growing to a harvestable biomass. This production needs to be both predictable, large scaled and with a degree of automation to be cost effective. The seedlings are grown on surfaces, typically ropes, nets or textiles to be transferred to the sea for biomass growth, and automation is important to ensure both efficiency and the quality of the fragile seedlings, as well as the safety of the cultivators when several km seeded ropes or thousand m^2 nets or textiles are to be deployed in the sea. Effective biomass harvesting must also be considered in the design of large seaweed farms to ensure optimized operations and logistics and since both ropes, nets and textiles are used as substrate different technological solutions are needed.

4.5.3 Seasonality

A main challenge in the development of production strategies is to obtain a high and predictable biomass productivity combined with a high content of the demanded components, like for instance carbohydrates that can be fermented to biofuel, proteins for fish feed or bioactive compounds that can be used in functional food. The Northern European seaweed species of interest for e.g. bioethanol production contain up to 60% carbohydrates per dry weight, but the seasonal variations of the carbohydrate composition are considerable due to variations in photosynthetic activity, nutrient availability and the age of the algae. In the spring microalgae consume most of the nutrients in the sea, leading to nutrient limitation for the seaweeds which in turn initiate accumulation of storage carbohydrates. In wild kelp the content of the storage compounds has a maximum in the autumn, whereas during the dark winter season the stored carbohydrates are utilized as energy source for protein synthesis and growth.

The storage carbohydrates are more easily utilized by microorganisms than the structural compound alginate and are thus attractive for fermentation to biofuels and chemicals. The biomass should thus ideally be harvested in the autumn. However, biofouling by epiphytes, both algae and invertebrates, during the summer months cause shading, nutrients competition, deterioration of the blades and up to 100% loss of the biomass if the seaweed is not harvested at the right time. This exemplifies one of the main challenges in industrial seaweed farming as the biomass not necessarily can be harvested when the chemical composition is at its optimum.

Figure 4.4. Sugar kelps covered by bryozoans in September. The tissue deteriorates, but new, undamaged tissue is growing out from the meristem (Photo: SINTEF Fisheries and Aquaculture).

4.5.4 Environmental interactions of seaweed cultivation

Seaweed cultivation is non-fed aquaculture and cultivated macroalgae will take up and utilize nutrient resources from surface waters (0-15 m) and by this affect the chemical and ecological state of open waters. Similar to the kelp forests and artificial reefs seaweed farms will attract many animals as they provide habitat and shelter for many benthic and mobile invertebrates and fish species. Especially fish larvae and juveniles can use seaweed farms as nursery areas in a critical life phase. Further, fish with benthic eggs may spawn on the kelp blades and large seaweed farms can thus function as recruitment area for wrasse juveniles and eventually enable a sustainable catch and use in salmon cages where these species clean the salmon for salmon lice. Quantification of the value for the environment and the economy that such an ecosystem service represents is important to supply the governmental authorities with facts, for establishment of administrative regulations that consider both the positive and negative interactions that large scale seaweed farming might have on the environment.

4.5.5 Genetics

There is a risk for spreading of spores from fertile farmed plants if these get sexually mature before the biomass is harvested. Also, small sporophytes, the thallus or parts of it can be lost and continue to grow and get fertile and genetic interactions can thus be expected. Cross breeding between domesticated and wild seaweed can be regarded as a possible negative interaction with the ecosystem and domestication through breeding of strains for certain traits can thus represent a threat against the wild populations. Information about the spreading potentials of spores can thus be important information in the selection of locations for the sea farms. Information about the genetic diversity within the different species to be domesticated is crucial to establish a knowledge base for guidance of the authorities in development of the regulations for macroalgae cultivation.

4.5.6 Disease problems

As in all aquaculture large monocultures like seaweed farms dispose for proliferation of microorganisms and viral, bacterial and fungal diseases may thus evolve and cause damage of the biomass quality. In Norway there is so far no documented experience with macroalgae diseases except from biofouling, and expertise about this topic will have to be established. Keeping the macroalgae in a good condition by optimized cultivation conditions and a proper harvesting regime is probably the most important measure to prevent disease. Monitoring of the growth and development of the macroalgae will help to reveal possible attacks, both from epiphytes and microorganisms, thus enabling harvesting in due time to avoid deterioration of the biomass.

4.5.7 Diversification of species

Industrial scale cultivation at sea will possibly be relevant only for a few species, at least on a short term. Tank cultivation will be needed for many species and enables a high degree of control compared to the sea as the environmental variables can be regulated more easily. Discovery of valuable components derived from species that so far not has been cultivated must be expected and will indeed call for development of species dependent cultivation technology in the future.

Figure 4.5. "Butare" (*Alaria esculenta*) is an interesting species for feed and food production (Photo: SINTEF Fisheries and Aquaculture).

4.6 R&D needs

Norwegian companies have already initiated R&D-projects on cultivation and bioconversion of seaweeds for bioenergy purposes. This work has revealed that despite the existence of large amounts of information about Norwegian seaweed species in the literature, fundamental knowledge needs to be built within several areas if a large scale seaweed cultivation industry should develop sustainably, in accordance with the needs from the society and the environment. Table 4.2 lists these needs and how they should be reached through research and development of technological solutions.

Table 4.2. R&D needed for industrial scaled macroalgae cultivation.

Need	R&D tasks	Research level
Cost effective production lines for macroalgae farms in the sea	1. Control of early life stages of different species	Basic
	2. Predictable large scaled seedlings production	Applied
	3. Cultivation site selection criteria	Basic
	4. Robust sea farms	Applied
	5. Deployment technology	Applied
	6. Automated biomass monitoring	Applied
	7. Harvesting and pre-treatment technology	Applied
	8. Logistics and biomass storage	Applied
Cost effective production lines for macroalgae cultivation in tanks	9. Control of early life stages of different species	Basic
	10. Adjustment of existing cultivation protocols	Applied
	11. Predictable production of high quality biomass	Applied
Predictable chemical composition of cultivated biomass	12. Composition of cultivated vs. wild macroalgae	Basic
	13. Effects of season	Applied
	14. Effects of environment	Applied
	15. Effects of cultivation in IMTA	Applied
	16. Measures to increased levels of demanded components	Applied
	17. 3D-modelling of site specific biomass productivity	Applied
Predictable biomass production	18. Selection of optimum species	Applied
	19. Definition of optimal growth conditions	Applied
	20. Seasonal impact on growth and productivity	Basic
	21. Environmental impact (nutrients, hydrodynamics, light)	Basic
	22. Strategies for cultivation in IMTA	Applied
	23. 3D-modelling for prediction of site specific biomass composition	Applied
Anti-biofouling measures	24. Improved biofouling resistance through improved macroalgae condition	Basic
	25. Optimizing of cultivation strategies including timing of deployment and harvesting	Applied
	26. Optimizing of water treatment in land based cultivation systems	Applied
	27. Development of monitoring and surveillance systems	Applied
	28. Intervention by mechanical or physical measures	Applied
Reveal the IMTA potential	29. Optimized localization of the macroalgae farms in IMTA	Applied
	30. Cultivation strategies for macroalgae reflecting seasonal variation in the biomass of the fed fish	Applied
	31. Reveal the potentials for increased catch of wild fish and invertebrates the macroalgae farm	Applied
Impact of large scale seaweed farming on the environment	32. Impact on the pelagic ecosystem	Basic
	33. Impact on the benthic ecosystem	Basic
	34. Genetic interactions between wild and cultivated macroalgae	Basic
	35. Impact on waves and water currents in IMTA	Applied
	36. Impact on the health of farmed fish and other organisms in IMTA	Applied
Up-scaling from experimental to commercial phase	37. For selected macroalgae species: Establish a best practise for industrial scale biomass production with predictable quality at defined localities	Innovation
	38. Optimized exploitation of the environmental conditions for fast growth, high biomass production, high levels om demanded components and low degree of biofouling	Innovation

4.7 Research competence and infrastructure in Norway for seaweed cultivation

Universities and research institutes with competence within cultivation of macroalgae are listed in Table 4.3. Norwegian research projects that are related to macroalgae cultivation and processing are presented in Table A.1 in Annex 1.

Table 4.3. Norwegian universities and research institutes with competence and infrastructure for macroalgae cultivation.

Norwegian R&D-institution	Key competence	Infrastructure
NTNU	Environment, Ecology, IMTA, Genetics, Macroalgae physiology, biology and biochemistry, Hydrodynamics, Marine structures and operations	Marine biological laboratories, Biotechnological laboratories, Mesocosm facilities, Research vessel, ROV, AUV
University of Bergen	Macroalgae biology, Environment, Ecology, Genetic interactions	Espeland Marine Biological Station with mesocosm facilities, temperature regulated rooms for algae cultivation, well equipped and DNA laboratories
University of Oslo	Macroalgae biology, Environment, Ecology, Gametophyte cultures	Marine biological laboratory for cultivation of gametophyte
Akvaplan Niva	Sea cultivation, Seedlings cultivation	Marine laboratories for seedlings cultivation
Bioforsk	Selection and breeding, Stress physiology and photobiology, Cultivation of different seaweed species (brown, red and green) from gametophyte stadium to sea farming, Cultivation technology, Macroalgae biology, Seaweed health in intensive systems, IMTA,	Marine biological laboratory with conditioned rooms and culture hall with up scaling possibilities up to 5000 l. Access to facilities for cultivation at sea. Water treatment. Automated light system. AutoAnalyzer for seawater analysis.
Institute of Marine Research	Environment, Monitoring of standing stocks	Research vessels
Møreforsking	Macroalgal biology & ecology, seedling cultivation, environmental monitoring & ecosystem interactions, IMTA, integrated management and spatial planning	Marine biological laboratory for cultivation of early life stages (pilot scale) and experimental facilities
NIVA	Environment, Monitoring, Macroalgae biology and ecology	Marine biological laboratories, Field station with aquarium and macroalgae mesocosms
SINTEF Fisheries and Aquaculture	Species selection, Seedlings cultivation of kelp, Gametophyte cultivation of kelp, Automation, Sea farming of kelp, Environment, Ecology, IMTA, Marine mdelling, Aquaculture constructions, Hydrodynamics, Up-scaling	Marine biological laboratory for cultivation of early life stages, Gametophyte laboratory, Pilot scale seedlings production (20km lines), Automated seedlings deployment, Water treatment, SINMOD, ACE salmon farm and cultivation sites

Several European research environments have extensive experience in cultivation of different macroalgae species and represent opportunities for complementary collaboration for Norwegian researchers and industrial companies. The most active institutes and universities within macroalgae cultivation are listed in Table 4.4. The list also includes some of the leading institutions outside Europe.

Table 4.4. Leading international universities and research institutes with important competence for macroalgae cultivation research and innovation.

European R&D-institutions	Competence area
National University of Ireland Galway (Ireland)	Macroalgae biology, cultivation biology for brown, red and green species (land and sea), deployment and harvesting technology, chemical composition and processing
Queens University of Belfast (UK)	Macroalgae biology, cultivation biology for brown, red and green species (land and sea), deployment and harvesting technology, chemical composition and processing
The Scottish Association for Marine Science (SAMS; UK)	Macroalgae biology, cultivation biology, IMTA, chemical composition and processing
Centre National de la Recherche Scientifique, Roscof (France)	Generic macroalgae biology and biochemistry, genetics, cultivation, chemical composition
CEVA (France)	Macroalgae biology, cultivation biology for brown, red and green species (land and sea), deployment and harvesting technology, chemical composition and processing
Aarhus University (Denmark)	Macroalgae biology, cultivation biology for brown, red and green species (land and sea), deployment and harvesting technology, chemical composition and processing
The Technical University of Denmark	Macroalgae biology, cultivation biology for brown, red and green species, chemical composition and processing
Danish Technological Institute (Denmark)	Sea cultivation, harvesting technology, processing
Alfred Wegner Institut (Germany)	Cultivation technology, off-shore environments
LEI Wageningen UR (The Netherlands)	Open sea cultivation, environmental factors
Fiskaaling (Faroe Islands)	Kelp cultivation, off-shore environments
AZTI Technalia (Spain)	Environmental factors, IMTA
Spanish institute of Oceanography (Spain)	Kelp cultivation, cultivation methods, environmental factors
CIMAR (Portugal)	Cultivation biology, brown and red species
R&D-institutions outside Europe	
University of Brunswick (Canada)	Kelp cultivation biology and technology, IMTA, industrial production
University Los Lagos (Chile)	Kelp cultivation biology and technology, IMTA, industrial production
Institute of Oceanology, Chinese Academy of Sciences (China)	Macroalgae cultivation biology and technology, industrial production lines
Yellow Sea Fisheries Research Institute (China)	Macroalgae cultivation biology and technology, industrial production lines

5 Seaweed biorefinery

5.1 Major constituents of seaweed

Common for all seaweed species is a high content of carbohydrates and minerals (ash). Due to the seasonal variations, the relative composition varies considerable (see also sections 4.1.1 and 4.5.3). In *Laminaria* and *Saccharina* carbohydrates constitute 40-70 % of the dry weight, ash 15-45 % , and protein 3-20 %. The variation ranges in green and red species are also high, e.g. 40-70 % carbohydrates, 12-27 % ash and 8-35 % protein in *Palmaria palmata*.

The carbohydrate fraction comprises structure polysaccharides, such as alginate in brown algae, and storage compounds, such as laminaran and mannitol in brown algae and starch in some red and green species. Brown algae also contain the sulphated polysaccharide fucoidan, small amounts of cellulose and significant amounts of polyphenols (see section 5.3).

A single large scale cultivation farm (60-100 ha) for kelp is envisaged to produce in the order of 10 000 tons wet weight (1 500 tons dw) biomass annually. At the season with maximum carbo-hydrate content, this will correspond to 900 tons carbohydrates, 300 tons ash and up to 300 tons protein. A cultivation area corresponding to the area currently used for salmon production (800 km^2), may provide 700 000 tons carbohydrates, 240 000 tons minerals and 240 000 tons protein.

Currently, alginate is the only compound that is isolated from macroalgae in Norway. The raw material is wild, harvested *L. hyperborea*, which has a high content of high-quality, G-rich alginate in the stipes. Norway has a strong, industry-driven R&D on production and applications of alginate, both for traditional and novel markets, including pharmaceuticals. This report does therefore not describe opportunities related to alginate, but focus on other potential products. However, cultivated biomass may also represent a future feedstock for the alginate industry.

5.2 Food

Macroalgae are already used extensively as food in coastal cuisines around the world and has been an important part of diets in China, Japan and Korea since prehistoric times. The growing globalization and adaptations of food culture worldwide give opportunities for cultivation and harvesting of macroalgae for food in Norway. One example is sushi, which the last 10 years has become a common part of our diet. As the public perception of local and sustainable food production increases, cultivated macroalgae used direct in food products may provide a significant contribution to Norwegian value creation. On a longer term, production of macroalgae for human consumption may give a contribution to the global, growing demand for food.

5.3 Protein as feed ingredient

New protein sources for animal and fish feed is demanded. As an example, a new prognosis for Norwegian aquaculture estimates the need for salmon feed to be 6 mill tons in 2050, almost 6 times higher than today (Olafsen et al., 2012). This feed will contain 30-50% proteins. New protein sources that can supplement the existing sources are thus crucial for a sustainable growth of the aquaculture industry.

Although carbohydrates constitute the major components in macroalgae, red and green species may contain more than 40 % protein of dry weight (Holdt and Kraan 2011). However, the species are small and lack the potentials for providing large biomass quantities through cultivation in the sea. Despite lower protein content, the kelp species *S. saccharina*, *L. digitata* and *A.esculenta* represent a larger potential due to the expected higher production volumes.

Seaweed protein has a higher content of essential amino acids than protein from most terrestrial plants and has a high nutritional value (Holdt and Kraan 2011). However, the protein of brown algae is yet less characterized than the red algal protein. The real protein content may also be overestimated, since the values cited from literature are "crude protein" (N x 6.25). Seaweed accumulate nitrate, and the protein factor for *Ulva* species is reported to be in the range of 5.12-5.65 (Shuuluka et al 2013).

Since the percentage of protein varies, the cultivation strategy must be tuned for harvesting when the biomass and the amino acid content are at its highest. Young tissue have the highest protein content, which may be an advantage, as cultivated sugar kelp may have to be harvested in June, when the biomass has been grown in the sea for only 4-8 months, in order to avoid biomass losses during the summer months due to fouling by epiphytic organisms (see section 4.5.3).

Studies on digestion and uptake of protein from brown algae by vertebrate animals seem to be scarce. The high polyphenol content of brown algae may represent a challenge. Polyphenols bind to protein and may limit the digestibility of the protein.

5.4 Minerals

Seaweed has a high mineral content, in the range 15-45 % of dw for *Laminaria* and *Saccharina* ("tare"), 18-30 % in *Fucus* and *Ascophyllum* ("tang"), and 10-30 % in red species (*Palmaria* and *Porphyra*) (Holdt & Kraan, 2011). The large variations are due to seasonal variations. The mineral content of *L. digitata* was 2.5 times higher in March (maximum) than in July (minimum) (Adams et al., 2011). Sulphate (SO_4^{2-}) and chlorine (Cl^-) are the dominating anions, while potassium is the dominating cation in the kelp species. The mineral fraction will be a part of the residues after extraction or fermentation of the organic fractions and could be utilized as a fertilizer.

A special feature of brown algae, particularly the Laminarales (*Laminaria* and *Saccharina* spp.) is their ability to accumulate iodine. The iodine concentration of *Laminaria* species is 30 000 times higher than in seawater (Bartsch et al., 2008). Iodine constitutes 0.25-1.2 % of the dry weight of *L. digitata*, with young plants up to 5 % of dw (Ar Gall et al., 2004). Historically, brown algae have been used as source of iodine, but the high content may also represent a limitation for a high intake of seaweed biomass. Historically, brown algae have been used as source of iodine, but the high content may also represent a limitation for a high intake of seaweed biomass.

5.5 Bioactive compounds and biochemicals

5.5.1 Polysaccharides

Macroalgal polysaccharides, including alginate, carrageenan, laminaran, fucoidans, ulvan and others possess a wide range of bioactive properties, such as anti-tumor, antiviral, anticoagulant, mucus protecting, LDL cholesterol reducing, anti-inflammatory and anti-hypertention effects (see reviews by Senni et al., 2011 and Holdt and Kraan, 2011). The content of the bioactive polysaccharides and phenols changes over the season (Jonsdottir et al., 2013). Particularly the sulphated polysaccharides, such as fucoidan, have been extensively studied with respect to their potential pharmacological properties (Wijesinghe and Jeon, 2012; Moghadamtousi et al., 2014).

The macroalgal polysaccharides could potentially be exploited as prebiotic functional ingredients for both humans and animal health applications. Prebiotics are non-digestible, selective fermented compounds that stimulate the growth and/or activity of beneficial gut microbiota which, in turn, confer health benefits on the host (O'Sullivan et al. 2010).

5.5.2 Other compounds

The brown algae have high contents of phenolic compounds, in particular the *Fucus* spp. and *Ascophyllum* (up to 12-14 % of dw), while the content of *L. digitata* and *S. latissima* is far lower

(<3 % of dw) (Holdt and Kraan, 2011). The different classes of phenols have multifunctional antioxidant activities and antibacterial and antifungal properties, as well as other bioactivities demonstrated in *in-vitro* and *in-vivo* studies (Dutot et al., 2012; Jimenez-Escrig et al., 2012; Baboa et al 2013; Hierholzer et al., 2013). The brown algal pigment, fucoxanthin, is a carotenoid with anti-oxidant activity and is also claimed to have anticancer effect (Moghadamtousi et al., 2014).

Macroalgae are also rich in taurine (Holdt and Kraan, 2011), which is essential for feline animals and has a large market in pet-foods. Taurine is important for salmon (Dragnes et al., 2009) and a recent report claims that taurine is essential for juvenile parrot fish *Oplegnathus fasciatus* (Lim et al., 2013).

The seaweed proteins can be a source of bioactive peptides with beneficial health effects for animals and humans (Freitas et al., 2013; Jensen et al., 2013).

5.6 Bioenergy and bulk chemicals

5.6.1 Liquid biofuels

The only commercially available biofuels today are "first generation" biofuels, mainly bioethanol and biodiesel produced from e.g. sugar cane and corn, and rapeseed, respectively. "Second generation" biofuels denotes fuels produced from non-food biomass, like wood and agricultural wastes. In Norway, as in other European countries with suitable areas for seaweed cultivation, the potentials of using seaweed biomass for production of the "third generation" biofuels have gained much attention. Due to the high carbohydrate content of the kelp species, sometimes up to 60% of the dry weight, they are an attractive biomass resource for production of ethanol, butanol and more advanced fuels.

Ethanol has been the first targeted liquid fuel from biomass (1^{st} and 2^{nd} generation), since the production technology already is well established. The production is based on the baker's yeast *Saccharomyces cerevisiae*, which is an efficient ethanol producer from glucose, but lack the ability to convert many other sugars to ethanol, such as the pentoses of lignocellulosic biomass, and alginate and mannitol of brown algae. Other yeast strains can convert mannitol, while very few microorganisms can ferment alginate to ethanol or other interesting fuels.

A high number of reports on ethanol production from seaweed have appeared the recent years, most of them only utilizing laminaran, mannitol and/or the small amounts of cellulose (Horn et al., 2000a; Horn et al., 2000b; Adams et al, 2009; Lee et al., 2013). Recently, the US company BAL, partly owned by STATOIL, have succeeded in production of ethanol from alginate by development of genetic engineered bacteria and yeast (Wargacki et al., 2012; Enquist-Newman et al., 2013).

Illustration of the ethanol production potential:

- An annual production yield of cultivated seaweed of 170 tons wet weight (ww) per ha, corresponds to 1530 tons carbohydrates per km^2, provided 15 % dry weight (dw) and 60 % carbohydrates of the dw.
- Utilization of all the three main carbohydrates with 80 % of the theoretical ethanol yield, will provide in the order of 225 kg ethanol per tons dw biomass, or 580 tons/km^2.
- A cultivation area of 800 km^2, *the same size as being used for today's aquaculture production*, would yield 470 000 tons ethanol.
- For comparison, the annual Norwegian consumption of gasoline is 1 mill tons, and of autodiesel, 3 mill tons.

5.6.2 Advanced fuels and chemicals

R&D is also on-going on development of processes for production of butanol from biomass. Butanol can be applied both as fuel and a platform chemical (see below). Butanol has a higher energy density than ethanol, and since butanol at fuel quality is not miscible with water, the same infrastructure as for gasoline can be applied, and a higher fraction can be added to gasoline. Butanol producing bacteria are able to utilize both mannitol and laminaran from brown algae (Hueseman et al., 2012). However, butanol producing organisms have lower productivity than the ethanol producing yeast, and their tolerance to high product concentrations are lower. These are challenges that need to be solved by optimization of either the microorganisms or the production technology before butanol production from any kind of biomass can be commercialized.

Large volumes of industry chemicals are currently produced from petroleum based raw materials, including solvents and chemical building blocks, or "platform chemicals", used in synthesis of polymers, e.g. for production of plastics. These chemicals have higher price than fuels, and may be an alternative, or a complementary product in a biorefinery. Among platform chemicals that can be produced from biomass carbohydrates for replacement of fossil based products, are diols (e.g.: 1,3-propanediol, 2,3-butanediol) and carboxylic acids (e.g.: lactic, fumaric and succinic acid).

5.6.3 Hydrothermal Liquefaction

Hydrothermal Liquefaction (HTL) is presently considered to be a promising alternative technology to conventional thermal processes, such as pyrolysis and gasification, for conversion of high-moisture biomass such as seaweed and residues from biological processing into biofuels and chemicals. The HTL process takes place in water under subcritical conditions, where the water behaves as solvent, reactant and catalyst. The kinetic pathways during HTL involve de-polymerization of the main biomass constituents, monomers decomposition by cleavage, dehydration, decarboxylation and deamination, and recombination of the reactive fragments. The products from HTL of biomass can be classified in four different categories: a liquid bio-crude consisting on an immiscible oil fraction and dissolved organic components in the aqueous solvent, a CO_2-rich gas phase and a solid phase (mainly in the form of char). The HTL product yields distribution, the chemical composition and the physical properties of the different phases vary widely depending on the composition and physical properties of the biomass feedstock and solvent, the process conditions and the presence of catalysts. HTL of biomass exhibits several remaining challenges for commercialization, including pressurized feeding of slurries, corrosion and salt precipitation. The upgraded oil product is in the diesel fuel range while chemicals can be extracted both from the water phase.

5.6.4 Biogas

Macroalgae is a suitable feedstock for biogas production. The biomass is more completely hydrolysed and converted than wood, since the macroalgae do not contain lignin and have low cellulose content. The methane yields from *L. digitata* and *S. latissima* is in the range 165-375 l/kg dw, corresponding to 25-55 l/kg ww (Tedesco et al., 2014; Debowski et al., 2013; Østgaard et al, 1993). In a long-term, large-scale experiment (*Laminaria* sp), the average yield was 22 l/kg ww (Hughes et al., 2012). Due to the high carbohydrate content of macroalgae, the methane yields can be increased by mixing the macroalgae with nitrogen-rich biomass such as fish or household wastes. This will also improve the quality of the mineral residues for use as fertilizers.

5.7 Processing

Continuous, year-round production is required for economic feasibility of a large scale production plant. The biomass will be harvested in a period of 2-5 months, when its composition is at its optimum. This implies that the seaweed biomass has to be stored and preserved. *L. hyperborea* harvested for alginate production in Norway (approx. 150 000 tons ww annually) is preserved with formaldehyde, which is not a viable option for later biochemical conversion. Other preservation methods applicable for several thousand tons have not been described. Drying could possibly be applied for small biomass volumes intended for high-cost products, but will be too expensive for high-volume/ low-cost products.

A seaweed based biorefinery should utilize the complete biomass for production of multiple products (Fig. 5.1). Production of biofuels or bulk chemicals, or isolation of protein, should be combined with extraction of high-value compounds. Organic residues can be fermented to biogas and cover part of the energy demands for the process, while the inorganic residues (minerals) can be utilized as fertilizers.

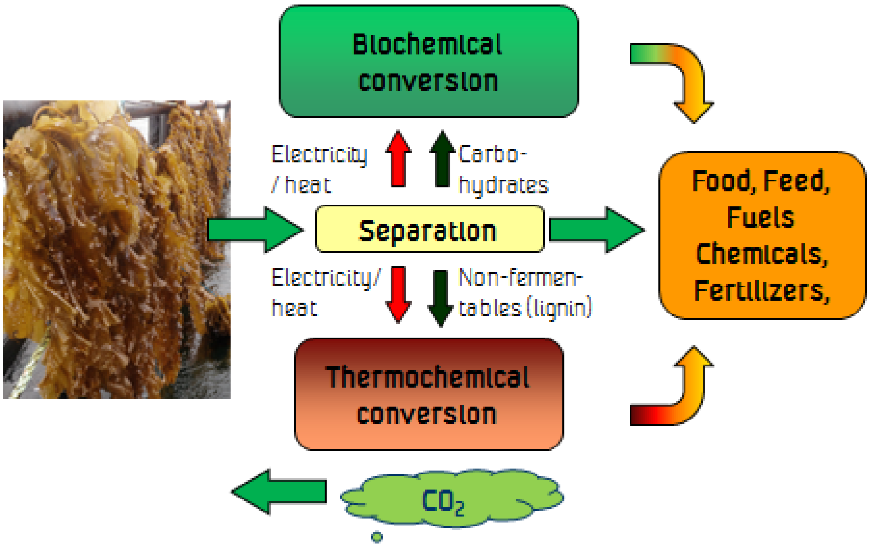


Figure 5.1. A biorefinery of seaweed biomass into multiple products.

A pre-treatment of the biomass is required in order to release and dissolve the compounds of interest. This implies de-sizing by milling, followed by mechanical, chemical or enzymatic methods for degradation of the cell walls and intercellular alginate matrix. A specific challenge is the high water content of macroalgae (75-90 %), which implies that further water addition should be minimized. This pre-treated biomass can be subjected to enzymatic hydrolysis and fermentation to fuels or chemicals, or applied for isolation of protein and high-value products.

5.8 Potentials and opportunities for a seaweed based industry

Although that the prospects for macroalgae biomass as an alternative to fossil resources for production of fuels has been the motivation for the recent year's increasing R&D efforts on mass cultivation of seaweed in Europe, the cultivations costs in a short-time perspective will be too high for the macroalgae biomass to be used as a carbon source only (see section 5.9). In order to establish a new macroalgal based industry in Norway, products that can generate economic feasibility on a short-time should therefore be given high priority. As the cultivation scale increases and costs decrease, the product range can be extended.

The products described in section 5.2-5.6 represent opportunities that should be explored. Table 5.1 summarizes the potential products and anticipated prices. However, more knowledge about the quantities and properties of the seaweed components, markets and prices are required in order to identify the product combinations with highest commercial potentials, see section 5.9-5.10.

In addition to the products that can be isolated from the biomass, or produced by fermentation of the carbohydrates, there is also a significant potential in further modifications of the isolated products. More valuable products can be generated by chemical or enzymatic modifications. For instance, the polysaccharides can be hydrolysed to oligomers, or substituted groups can be introduced or removed. Basic research on development of new enzymes for biomass processing and modification of marine polysaccharides are currently on-going as part of the Biotek 2021-programme.

Table 5.1: Potential products and anticipated price from macroalgal species suited for cultivation in Norway.

Compounds	Potential products and/or markets	Potential price*
Unprocessed plants	Food	Low-medium
Seaweed extracts	Cosmetics	Medium
Carbohydrates /	Thickening, viscosity enhancer etc.	Medium
polysaccharides	Prebiotics	Medium
	Pharmaceuticals	High
	Fermentation substrate (fuels, chemicals)	Low
Protein	Animal and fish feed	Low-medium
	Bioactive peptides (food/feed)	High
Polyphenols	Antioxidants (food/feed, cosmetics)	High
	Antimicrobials (food preservation, antifouling etc)	Medium-high
Ash	Fertilizer	Low-medium
	Valuable minerals	Medium-high

*: Low: < 10 kr/kg; Medium: 10-100 kr/kg; High: >100 kr/kg

5.9 Challenges and limitations

5.9.1 Feedstock costs and competition with products from other feedstocks

For bulk products (high volume, low price) like fuels and chemical from conversion of the carbohydrates, the cultivation costs are the main limitation for realization. The feedstock costs may also be a limitation for utilization of the protein for feed. The current price for LT fish meal is 10.50 kr/kg, and for soy protein 4.30 kr/kg (Felleskjøpet Fôrutvikling, February 2014), while the sugar price (sucrose, starch) is below 3 kr/kg. Table 5.2 illustrates the required feedstock costs for generation of sugar and protein at competitive prices. Costs for biomass processing are not included. On the other hand, value generated from utilization of other compounds from the biomass may allow lower prices on sugars and protein. However, for these products (higher-price / lower-volume) it is not unlikely that compounds with similar, or even better, properties can be produced cheaper from other raw materials. It is therefore of crucial importance to identify product combinations that can make a multiple product biorefinery economic feasible.

Table 5.2: Product prices as a function of the cultivation costs, exclusive costs for processing of the biomass to make the sugars available for conversion, or costs for protein isolation.

Feedstock costs		Corresponding product price [NOK/kg]		
NOK/tons ww	NOK/tons dw (15 % dw of ww)	Sugar (40 % of dw)	Sugar (60 % of dw)	Protein (10 % of dw)
200	1333	3.33	2.22	13.33
500	3333	8.33	5.56	33.33

5.9.2 Product identification

In order to identify products with a commercial potential, a comprehensive characterization of the content of micro- and macro-constituents of the Norwegian seaweed resources and their seasonal and environmental variations is required. Currently, only the major carbohydrates have been well characterized, and even for these, a complete understanding of their variations with age, season and nutrient availability is lacking. High priority should be given to a characterization (quantities and amino acid composition) of the protein fraction of *S. latissima*, *L digitata* and *A. esculenta*. With respect to potential high-value products, seaweeds seem to be able to solve more or less all kinds of health problems of the population. A critical attitude to the published claims, and reliable documentation of the bioactive properties is needed. In parallel with more documentation, market analyses for the respective components are required. Further, as discussed in section 4.5.3, controlled cultivation conditions to obtain a high, and predictable content of the desired compounds is required.

5.9.3 Process development

Existing industrial processes are directed at isolation of single compounds, such as polysaccharides. Production of multiple products from seaweed biomass as part of a biorefinery is more challenging, since high yield extraction of one compound may compromise a cost-efficient isolation of other compounds, or dilute the process stream to an extent that excludes conversion of the carbohydrates by fermentation. Therefore, development of new processing technologies combining extraction, conversion and separation processes for multiple products are needed.

5.9.4 Food and feed safety

For application in food and feed, the high mineral content and potential high levels of heavy metals (lead, cadmium, tin, mercury etc.) may limit the acceptable intake of biomass, or a reduction of the mineral content by a pre-processing may be required. To which degree the content of heavy metals is affected by the cultivation location should also be investigated. Also the high content of iodine in the Laminariales (see section 5.3) may represent a limitation for food and feed applications.

5.10 R&D needs

The R&D-needs for development of new, seaweed biorefineries, as discussed in section 5.9, are summarized in Table 5.3.

Table 5.3. R&D needed for industrial utilization of compounds from seaweeds.

Need	R&D tasks	Research level
Market analysis and economical potential for products from macroalgae	1. Investigate the markets (volumes, prices) for the different product segments	Applied
	2. Evaluation of potential incomes based on the market analysis and expected production quantities	Applied
Food	3. Consumer investigations and market development	Basic
	4. Evaluation of food safety parameters (biological, heavy metals, iodine etc.)	Basic/Appl
	5. Product development	Applied
Contents and properties of potential valuable compounds	6. Quantification and structure elucidation of polysaccharides other than alginate (fucoidan, laminaran) as a function of species, age, season and location	Basic
	7. Characterization and quantification of the different phenolic compounds in the relevant species a function of species, age, season and location	Basic
	8. Determination of the bioactive properties of fucoidans and the different classes of phenols (antimicrobial, antioxidant)	Basic
	9. Identification and quantification of other low-molecular weight compounds, such as pigments	Basic
	10. Establish rapid analytical methods for quantification of the most interesting compounds (including required extraction protocols) to be used in cultivation studies	Applied
	11. Evaluate potential applications, based on the market analysis	Applied
	12. Develop products for applications as functional food, other food/feed ingredients, cosmetics etc.	Applied
Technologies for storage and pre-processing	13. New preservation technologies suited for large biomass volumes	Applied
	14. Processes for release and solubilisation of the desired components, including new enzymes and enzymatic processes	Appl/basic
Utilization of proteins from macroalgae	15. Quantification of total protein and amino acid composition in selected species as a function of age, season and location	Basic
	16. Development of processing technology for protein isolation	Applied
	17. Investigate the protein digestibility, including the impact of the processing methods	Basic/Appl
	18. Evaluate the role of polyphenols and other potential antinutrients, and the need for removal of these	Basic
	19. Mapping of potential toxic compounds (heavy metals etc)	Basic/Appl
	20. Protein availability and feed conversion studies for different animal species at different life stages.	Applied
Processes for isolation of protein and higher-value compounds	21. Development of processes for isolation of the protein fraction	Applied
	22. Development of isolation and separation processes for other valuable compounds	Applied
	23. Integration of processes for production of multiple products	Applied
Production of fuels or chemicals from the carbohydrates	24. New hydrolytic enzymes	Basic
	25. Genetic engineered microorganisms for efficient conversion of the macroalgal carbohydrates	Basic
	26. Reactor design and fermentation process development	Applied
	27. Consolidated bioprocessing for integration of pre-	Basic/Appl

	treatment and fermentation 28. Process intensification through integration of fermentation and in-situ separation processes Advanced down-stream processing for cost efficient separation of compounds	Basic/Appl
Processes for Hydrothermal conversion of macroalgae to biofuels	29. HTL process optimisation 30. Catalyst development 31. Upgrading	Applied Applied Applied

5.11 Research competence and infrastructure in Norway for seaweed processing

Universities and research institutes with competence within and infrastructure for seaweed processing are listed in Table 5.4. Norwegian research projects that are related to macroalgae cultivation and processing are presented in Table A.1 in Annex 1.

Table 5.4. Norwegian universities and research institutes with competence and infrastructure for macroalgae processing.

Norwegian R&D-institution	Key competence	Infrastructure
NMBU	Biogas, Enzymes for biomass processing, Animal and fish feed (production technology and biological evaluations)	Biomass pretreatment facilities, Enzyme reactors, Analytical tools, Proteomics platform
NTNU	Biopolymers, Biopolymer-modifying enzymes, Food technology, Molecular biology, Chemical Engineering, Chemical catalysis, Enzymatic hydrolysis, Protein chemistry, Processing of rest raw materials	Characterisation of proteins (solubility properties, molecular weight distribution), Functional properties (water holding, emulsion, enzymatic activities, oxidation of proteins), Selected bioactive properties (blood pressure reducing, antioxidative), Rheology lab, NMR
UiT	Marine bioprospecting, Bioactive compounds and drug discovery	Marine biobank, Medium/high-through put platform for screening and identification of bioactive compounds, Protein structure determination platform
Bioforsk	Seaweed for human consumption, Use of seaweed and seaweed products for agricultural purposes such as: animal feed ingredient and feed additives, fertilizer, soil conditioner and organic farming	Research animal facilities, including respiratory chambers for small ruminants, and land surface
SINTEF Energy	Bioenergy, Thermal processing of biomass, Hydrothermal liquefaction, Pyrolysis	Batch and continuous lab-scale reactors, TGA, Element analyses. CFD and kinetics modelling, Techno-economic evaluations
SINTEF Fisheries and Aquaculture	Processing of rest raw materials, Lipid technology, Protein technology, Food	Enzymatic hydrolysis equipment, NMR, Mobile production plant

	technology	for oil and proteins, Pilot plant for refining and modification of marine oils
SINTEF Materials and Chemistry	Microbial and enzymatic processes, Biopolymers, Biopolymer-modifying enzymes, Molecular biology, Bioprospecting, Chemical engineering, Separation technology, Chemical catalysis, Process design and optimization, Technical and Economical evaluation	Fermentation laboratories, High-throughput screening, Mass-spectrometric analyses, Downstream processing (membrane filtration etc.)

Table 5.5 lists international universities and research institutes with comprehensive experience and outstanding competence of relevance for cultivation of cold water macroalgae species, representing the most significant opportunities for collaboration that can facilitate the development of the Norwegian cultivation industry.

Table 5.5. International universities and research institutes with important competence for macroalgae utilzation/processing/products.

European R&D-institutions	Competence area
National University of Ireland Galway (Ireland)	Utilization of seaweed as animal feed
The Scottish Association for Marine Science (UK)	Anaerobic digestion, biogas
Centre National de la Recherche Scientifique, Roscof (France)	Chemical composition and processing
Aarhus University (Denmark)	Chemical composition and processing
The Technical University of Denmark	Macroalgae biology, cultivation biology for brown, red and green species, chemical composition and processing
Danish Technological Institute (Denmark)	Biorefinery concept, fermentation to biofuels, extraction, separation,
Wageningen UR (The Netherlands)	Fermentation to biofuels
ECN (The Netherlands)	Pre-treatment, thermochemical processing
MATIS (Iceland)	Valuable compounds (bioprospecting), enzymes for degradation and conversion
CEVA (France)	Development of products from macroalgae (food, feed, cosmetics etc.)

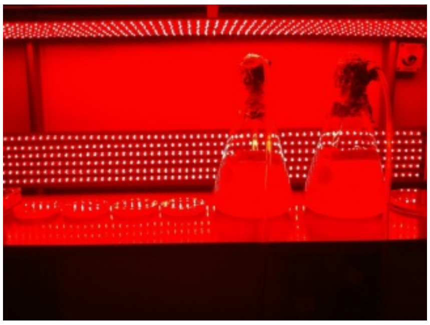


Figure 5.2 Culture of kelp gametophytes kept in red light (Photo: SINTEF Fisheries and Aquaculture).

6 Seaweed research in Norway

The establishment of the Norwegian Institute for Seaweed Research in 1949 was a starting point for the Norwegian seaweed industry, and the Norwegian research on algae polymers is still acknowledged as world leading. Norway is also internationally reputed for the management of our wild seaweed resources that are harvested for industrial purposes. Cultivation experiments at small scale for testing of the biomass potentials as well as for ecological research has been performed since the 80's. After 2000 the interest for cultivation of kelp increased for two reasons; biofuel production and IMTA. We now experience a broad interest for different species and applications in Norway and this is reflected in the diverse R&D-project activity. Table A.1 in Annex 1 lists R&D-projects carried out by Norwegian since 2000 and although not 100% complete it illustrates a large width and depth.

This research work was appointed by Innovation Norway in collaboration with the Norwegian Ministry of Fisheries and Coastal Affairs and demonstrates the interest and willingness of the Norwegian Government to contribute to a growth in the seaweed based economy. The research work by Handå et al. (2009) on cultivation of kelp for bioenergy purposes revealed the great potentials Norway has for cultivation of seaweeds, both at off-shore conditions and in IMTA. Since 2009 a Norwegian knowledge base concerning cultivation biology and technology has been established, and the competence on different processing methods improved considerably. This activity was managed through the Norwegian Seaweed Technology Center at SINTEF and NTNU in Trondheim and illustrates how a focused priority can create comprehensive amounts of knowledge and competence of high value for both the industry and the academia, nationally and internationally. In this period a considerable competence in seaweed cultivation and application is also established by Bioforsk Nord in Bodø, especially for the less utilized and studied species than the kelps. These two research environments are thus both complementary and constitute a core competence needed for further development of the seaweed based industry in Norway. Their international networks are broad and constitute leading research institutions along the whole value chain, allowing for fruitful international collaboration.

7 Recommendations

Three priority areas are suggested below. Ideally these areas should be developed in parallel, but with different speed as the need for fundamental research differs. Focused, long term research is an indisputable need and must be guaranteed to avoid collapse of industrial companies starting on wrong premises and with lack of adequate competence, as well as of research groups which depend on a degree of predictability. The funding of the research on cultivation and biorefinery needs to be strengthened and coordinated between the programs in the Research Council or ideally assembled in one program for marine bioproduction and biorefinery. Based on this research work we suggest three priority areas:

- **Priority area 1 – Biomass production**

On a short term (to get started) the biggest potential for creating business based on cultivated seaweed in Norway is to:

1) utilize sugar kelp, as this is the species with best known cultivation technology (closest to domestication) and thus will be available in large quantities

2) develop preservation techniques to stabilize the biomass and thus allow for year-through processing of biomass harvested once per year
3) produce "low-technological", demanded products like energy (e.g. biogas) or proteins with well identified markets although these products have low economic value

The authorities must get access to the information needed to make regulations specific for seaweed aquaculture.

- **Priority area 2 – Biorefinery**

In parallel to the cultivation technology, technology for efficient conversion of the biomass needs to be developed, partly through adaption form other fields, or new innovative processes. These processes needs to be integrated early in a holistic biorefinery concept which allows for cost, resource and energy efficient production which is optimized for different macroalgae species and product families to be produced. Initially, high-value products should be focused, as this can be the key for profit. However, economics of a plant will be a trade-off between production volume and product price, thus understanding of interacting value chains need be prioritized.

- **Priority area 3 - Species diversification and product quality optimization**

On a long term the Norwegian seaweed industry should develop into a broad range of products and markets, based on a (limited) number of cultivated seaweed species. Cultivation technology for a number of species should make industrial scale production possible. The processing of different components and products should be refined to ensure the optimum quality of the products. Flagship plants demonstrate cost effective biorefinery.

8 A future vision for a new Norwegian bioeconomy

A yearly harvest of 17,000 tons cultivated seaweed per km^2 represents a large and sustainable biomass with great potentials as an alternative non-food and non-petroleum feedstock for a long range of important products. Such a biomass production is possible in the sea with 2-3 of our kelp species. Other less productive or more fragile species are also highly interesting as feedstock for high value products and some of them attractive in the production of healthy human seafood.

A vision for a new seaweed-based bioeconomy:
Cultivation of macroalgae at the lowest trophic level, using only sunlight and nutrients from the sea while taking up CO_2, may have a neutral carbon footprint and the biomass will contribute significantly to meet the demand for food, feed, materials, chemicals, fuels and pharmaceuticals in near future. Through a new bioeconomy based on cultivated macroalgae Norway will establish a future feedstock bypassing the competition with land-based agricultural resources and at the same time contribute to the replacement of fossil resources. This blue bioeconomy will strengthen Norway's role as the leading seafood nation as well as a leading supplier of marine, sustainable biomass.

9 Supplementary information

A lot of supplementary information about cultivation and applications of seaweeds can be found in open reports and web-sites and a selection of these are listed below:

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11 Annex 1

Table A.1. Research projects in Norway since 2000 on cultivation and application of seaweeds as a resource in bioeconomy (list may not be complete).

Project name	Year	Project leader (institution)	R&D-collaboration (national)	R&D-collaboration (international)	Industrial collaboration	Financing organ/co-financing
Marine biomolecules; properties and mechanisms	2000-2004	UiT	SFH, NIFA, NTNU			NFR
Effects of a newly introduced benthic red alga on biodiversity and community structure in the coastal zone of Norway	2003-2004	UiB				NFR
Bio-purification - Reducing the environmental impact of land based aquaculture through cultivation of seaweeds	2004-2006	National University of Ireland, Galway (IE)	SFH		Oyster Creek, Oranmore, Co. Galway (IE)	EU– INTERREG
Sukkertareprosjektet	2004-2008	NIVA	UiO			SFT/Klif
Integrate- Integrated open seawater aquaculture, possibilities of sustainable culture of high productive areas	2006-2011	SINTEF Fisheries and aquaculture	NTNU	Cawthron Institute (NZ), National University of Ireland (IE), University of Kiel (DE), University of New Brunswick (CA), Yellow Sea Fisheries Research Institute (CN), University Los Lagos (CL)	Salmar, Lerøy	NFR
Causes and consequences of a large-scale shift from sugar kelp (*Saccharina latissima*) to ephemeral algae and implications for management	2007-2011	NIVA	UiO, UiB, HI	Roskilde University Center (D)		NFR
Cultivation of seaweed for biofuel	2008-2011	SINTEF Fisheries and aquaculture			Statoil	Statoil
RESTORE-Habitat restoration in overgrazed areas on the northern Norwegian coast	2008-2013	NIVA	UiO	Roskilde University Center (D), University og Maine (US), Univerity of Ausin Texas (US), University of		NFR

				Tokyo (J)		
Ocean Biopower- farming seaweed for energy	2008-2010	SINTEF Fisheries and aquaculture			SES	NFR/SES
EPIGRAPH project	2008-2011	IMR	UiB			NFR
Dyrking og anvendelse av tare, med spesiell fokus på bioenergi i nordområdene	2009	SINTEF Fisheries and aquaculture				FKD
Ocean Biopower- Biofuels from farmed seaweed	2009-2010	SINTEF Materials and chemistry			SES	NFR/SES
NETALGAE- Inter-regional network to promote sustainable development in the marine algal industry	2009-2012		Bioforsk	Indigo Rock Marine Research (UK) m.fl.		EU –INTERREG, Nordland fylkeskommunen
MacroBiomass- A knowledge base for large scale cultivation of macroalgae biomass in Norway	2010-2012	SINTEF Fisheries and aquaculture	UiO, NTNU	Sylter Algenfarm (DE), Marifood (DK)	SES	NFR* Natur og næring
Videreutvikling av indikator for sukkertare i Norsk Naturindeks	2011-2012	NIVA				DN
Stortareskog som indikator i Norsk Naturindeks	2011-2013	NIVA				DN
SeaBreed- Industrial seaweed seedling production for large scale offshore cultivation process	2011-2013	SINTEF Fisheries and aquaculture	NTNU	CIIMAR (PT), Stolt Seafarm (ES)	SES	NFR/SES
SeaweedTech	2011-2013	SINTEF Fisheries and aquaculture			SES, Aqualine	NFR/SES
SeaweedStar - Offshore cultivation of seaweed	2011-2013	Seaweed Energy Solutions		CIIMAR	Stolt Seafarm, Winds Enterprises	EU- Eurostars
Utviklingsprosjekt Alger	2011-2004	Norges Vel				Norges Vel
Norsk senter for tang- og tareteknologi	2012	SINTEF Fisheries and	NTNU, SINTEF M&C			Reg Midt

		aquaculture				
Exploit- Exploration of nutrients from salmon aquaculture	2012-2014	SINTEF Fisheries and aquaculture	NTNU, HI, Bellona	Fisheries and Oceans Canada (CA), Wageningen UR (NL), Universidad De Los Lagos (CL), University of New Brunswick (CA), Universidade Federal De Santa Catarina (BR), Yellow Sea Fisheries Research Institute (CN)	Marine Harvest	NFR
DYMALYS	2012-2014	Blue planet			Leroy Seafood Group, Bicotec, Lysefjorden Forskningsstasjon, EWOS Innovation, Bellona, Sylter Algenfarm , IVAR	Lerøy og Rogaland Fylkeskommune
Dyrking av høykvalitets makroalger for Algea	2012-2013	SINTEF Fisheries and aquaculture			Algea	VRI/Algea
Val algeprosjektet	2013-	Val vgs	Bioforsk		Norges Vel, Bellona	Ytre Namdal næringsfond
PILOTSTUDIE PÅ BIOENERGI FRA TARE	2013-2014	Seaweed Energy Solutions	Akvaplan-niva, UiT		Lerøy Aurora, Sjurselv AS	RDA Troms fylkeskommune
Alger til mat i Solund	2013-2014	Norges Vel			Hortimare, Fremtidens Mat, Solund Mat	Sogn og Fjordane fylkeskommune
Markedsvurdering for bærekraftig Algedyrking	2013-2004	Norges Vel	IMR		Salmon Group, Hortimare, Engesund fisk, Smartfarm	Regionalt utviklingsprogram
Handling, storage and preservation of cultivated seaweed biomass for fuel production	2013-2015	Seaweed Energy Solutions	SMC		Statoil, SES	NFR/SES
Industrial-Scale Harvest and Transport of Seaweed for Biofuel	2013-2015	Seaweed Energy Solutions	SFH		Biotrål, Statoil, SES	NFR/SES
Biobased products from sustainable resources	2013-2016	SINTEF Materials and chemistry	SINTEF Energy, SFH			SINTEF
Forskningsbehov knyttet til dyrking av og utnyttelse av tang og tare	2012-2013	SINTEF Fisheries and aquaculture				IN

Trofôr - Program for utvikling av nytt fiskefôr til laks	2012-2013	Bioforsk	Nofima		Gifas	Privat
Isolation and characterization of Norwegian red algae suitable for commercial mariculture	2012-2013	Bioforsk			Gifas	MABIT/Gifas
IDREEM- Increasing Industrial Resource Efficiency in European Mariculture	2012-2015	Scottish Association for Marine Science (SAMS) (UK)	Bioforsk		Viking Fish Farm (UK), Scottish Salmon Company (UK), Suf-fish Aquaculture	EU- FP7
Biprodukter til bioproduksjon - Resirkulering av lokale avfallsstrømmer fra industri, fiskeoppdrett og landbruk	2013	Bioforsk			Elkem, Sisomar	NFR
Integrert havbruk: tareanlegg som rensestasjon for avløpsvann fra landbaserte anlegg	2013	SINTEF Fisheries and aquaculture			Smøla Klekkeri og settefiskanlegg AS	RFF-Midt
Development of a new fish feed concept based on raw materials from aquaculture and fish industry – development of protocols for production	2013	Bioforsk	UiN			MABIT
Marknadsvurdering for bærekraftig algedyrking i IMTA-anlegg	2013-2014	Norges Vel	Møreforskning		Hortimare AS, Salmon Group, Engesund Fiskeoppdrett AS, Smart Farm AS	Hordaland Fylkeskommune
Tilrettelegging for dirking av butare i Trøndelag	2013-2014	SINTEF Fisheries and aquaculture			Bygda 2.0, Nesset Sjømat	VRI
Establishing mariculture of red algae for food production in Northern Norway	2013-2015	Bioforsk	Nofima	Université de La Rochelle	Gifas	NFR
INVASIVES- Invasive seaweeds in rising temperatures: impacts and risk assessments	2013-2016	UiB				NFR
MacroPlatform- Etablering av en internasjonal	2014	SINTEF Fisheries and aquaculture				NFR

samarbeidsplattform for helhetlig utnyttelse av dyrkede makroalger					
Mat fra dyrket tare: Produksjon av norsk "wakame" fra butare	2014-2015	SINTEF Fisheries and aquaculture	Bygda 2.0, Nesset Sjømat		RFF-Midt

Abbreviations

NFR: The Research Council of Norway
RFF: Regionalt Forskningsfond
VRI: Virkemidler for regional FoU og innovasjon
MABIT: selvstendig, næringsrettet FoU-program innenfor marin bioteknologi i Nord-Norge
IN: Innovasjon Norge
RDA: næringsrettede midlene til regional utvikling
DN: Direktoratet for Naturforvaltning (Miljødirektoratet)
SFT: Statens Forurensningstilsyn (Klif)
SFH: SINTEF Fisheries and Aquaculture
SMC: SINTEF Materials and Chemistry
SES: Seaweed Energy Solutions
UiB: University of Bergen
UiO: University of Oslo
UiN: University of Nordland
UiT: University of Tromsø
NIVA: Norwegian Institute for Water Research
IMR: Institute of Marine Research