Nordic Council of Ministers

Nordic Working Paper

Joint Nordic Seaweed Innovation Network

Report prepared by:
Anna Sauermilch Sørensen, SINTEF Ocean
Annette Bruhn, Aarhus University
Sophie Steinhagen, University of Gothenburg

This working paper was funded by the Nordic Council of Ministers. However, the content does not necessarily reflect the Nordic Council of Ministers' views, opinions, attitudes or recommendations

NA2025:906
ISSN 2311-0562
http://dx.doi.org/10.6027/NA2025-906

Nordic Council of Ministers
Nordens Hus
Ved Stranden 18
DK-1061 Copenhagen
www.norden.org

Photo: Sophie Steinhagen

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Prepared for:

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Authors:

Anna Sauermilch Sørensen, SINTEF Ocean
Annette Bruhn, Aarhus University
Sophie Steinhagen, University of Gothenburg

Contact person:

Anna Sauermilch Sørensen
anna.sorensen@sintef.no

A green revolution from the ocean in a changing world

The world is facing significant challenges in the coming decades. A growing population, increased demand for food and resources, the climate crisis and the degradation of natural ecosystems leading to loss of biodiversity are among some of the challenges. Addressing these issues requires innovative solutions and a transition toward sustainable and regenerative resource systems.
In recent years, seaweed has gained increasing attention as a climate- and environmentally friendly marine bioresource with broad industrial potential. Seaweeds can be cultivated in the sea and in land-based systems and have the advantages of requiring limited resources of freshwater and arable land, and no pesticides. In addition, seaweed cultivation has the major advantage of enabling emission capture and utilisation, which means that nutrient rich waste sources, such as industrial waste streams from food and energy production, as well as eutrophic seawater can serve as nutrient source enabling at the same time a cleaning of waste water and re-use of nutrient resources into new biomass. Seaweeds represent a rich source of fibres, proteins and bioactive compounds such as antioxidants, vitamins, and minerals, making it suitable for applications across a wide range of sectors, including food, animal feed, pharmaceuticals, cosmetics, fertilisers, and biomaterials. In the marine environment, a beneficial aspect of seaweed cultivation is its potentially positive impact on the surrounding ecosystems (United Nations Environment Programme, 2023). Seaweed can absorb and store nutrients and carbon dioxide (Krause-Jensen et al., 2018), contributing to the mitigation of eutrophication and local climate effects e.g. mitigating ocean acidification and de-oxygenation. Additionally, seaweed farms provide habitat and shelter for juvenile fish and other marine organisms, and a regenerative cultivation practice may enhance biodiversity. Cultivation of seaweed can be integrated into existing marine infrastructure, such as wind farms and aquaculture facilities, allowing for synergistic ocean hubs co-locating food and energy production in certain areas, allowing protection of other areas, and potentially reducing the overall use of labour and energy, implementing a multi-use approach (Schupp et al, 2019. Maar et al, 2023). The vast and diverse marine areas in the Nordic region offer ideal conditions for seaweed farming and the two largest European seaweed producing companies are based in Nordic countries. At the same time the land-based seaweed production is advancing in the Nordic countries in connection to an expanding land-based fish production. Consequently, the Nordic countries hold significant potential to become leading producers of seaweed in Europe.

Through the Joint Nordic Seaweed Innovation Network project, knowledge and experiences from seaweed cultivation have been shared among Nordic stakeholders from industry and R&D in the Nordic countries, and together, good practices, challenges, and new ways forwards have been explored to jointly raise up to the massive challenge.

Ulva spp. cultivation in the Nordic region

The species of focus in this project have been the *Ulva* species (*Ulva* spp.), a group of species belonging to the green algae (Chlorophyta). The Ulva species show high tolerance towards fluctuating environmental factors such as temperature, light intensity, salinity, and nutrient availability, and are suitable for cultivation in the Nordic waters, where environmental conditions are characterised by large temporal and spatial variation. Due to the high tolerance, rapid growth rate and efficient nutrient uptake of the *Ulva* species, these species hold a huge potential for cultivation and application in industries and are both suitable for cultivation on land and in the sea (Bruhn et al., 2011; Steinhagen et al. 2021; Steinhagen et al. 2022). The high growth rate makes *Ulva* species ideal for bioremediation of eutrophicated marine waters or various types of industrial wastewater (Nielsen et al. 2012. Sode et al, 2013. Stedt et al, 2022. Larsen-Ledet et al, 2025). Several experiments have demonstrated good growth rates in industrial wastewater (Stedt et al. 2022), and cultivation of *Ulva* spp. could be a method for remediating nutrient rich waters and turning otherwise wasted resources into valuable biomass.

In Sweden, the cultivation of *Ulva* species has emerged as a rapidly developing field within marine biotechnology and sustainable aquaculture. At present, the predominant species cultivated under fully marine conditions is *Ulva fenestrata*, which has demonstrated high productivity and robustness in offshore environments (Steinhagen et al. 2021). Concurrently, ongoing research efforts are directed toward optimizing cultivation protocols for *Ulva intestinalis* under lower salinity regimes, aiming to enable large-scale biomass production in brackish environments such as the Baltic Sea. Currently, *Nordic Seafarm AB* represents the leading industrial actor cultivating *Ulva* on a commercial scale in Sweden. The company operates in fully marine open-ocean systems and joined the JNSIN consortium – leading to fruitful discussions, scientific exchange, and supported with a site visit to their hatchery facilities. Overall, *Ulva* research and industry in Sweden are gaining significant momentum, reflecting an increasing recognition of the genus as a versatile and sustainable resource for food, feed, and biotechnological applications.

In Denmark, the exploitation of *Ulva* species is expanding via three pathways: 1) Land-based cultivation in connection to nutrient rich waste streams; 2) cultivation in the sea and 3) harvest of massive blooms of *Ulva* in nature, the so-called 'Green tides'. The land-based cultivation of *Ulva* has developed since 2008 exploring the potentials in utilising both carbon and nutrient rich waste streams such as fluegas from powerplants and fish production, and nutrients from biogas production (Sode et la, 2013), agriculture (Nielsen et la, 2012), and land-based fish production (Larsen-Ledet et al, 2025). One company, PureAlgae A/S, has developed scalable cultivation systems for R&D as well as commercial solutions since 2018, and are presently installing demonstration systems in connection to land-based production of both fish and shrimps in Denmark and Germany. The species used in the land-based systems is predominantly *Ulva compressa*. The production of *Ulva* on long-line systems has been tested in different marine areas since 2017, both with commercial aquaculture producers, and as part of R&D projects, also involving offshore wind farms, as part of larger national and international research projects (Steinhagen et al, submitted. Larsen-Ledet et al, in prep). In marine systems, the species used is predominantly *Ulva fenestrata in high saline waters and Ulva intestinalis* in more brackish waters. The harvest of green tides has been tested in Denmark since 2018, as a means for both nature restoration of highly eutrophic fjord systems (Bruhn et al, 2020), but also as a process for re-using the nutrient resources lost from land to the coastal environment into protein for food and feed purposes. The extraction and purification of the *Ulva* protein have been significantly improved and scaled up (Juul et al, 2021, 2022, 2023, 2024. Nissen et al, 2024), and life-cycle analyses have contributed to identifying the process steps needing improvement for optimising environmental and economical sustainability (Thomsen et al, submitted).

The Norwegian macroalgae industry is expanding, supported by numerous research initiatives focusing on cultivation techniques, automation, and integration into existing aquaculture systems. A particularly promising approach is the co-cultivation of seaweed alongside fish production, given Norway's position as a global leader in farmed fish. Co-cultivation can be implemented both in land-based recirculating aquaculture systems (RAS) and in the sea through Integrated Multi-trophic Aquaculture (IMTA) farms. Despite these opportunities, research on the cultivation of *Ulva* spp. remains limited, and large-scale production experience is scarce. Most trials to date have been conducted in land-based systems. Experiments by SINTEF Ocean and NTNU have demonstrated that *Ulva* spp. can serve as an effective biofilter in RAS facilities, contributing to nutrient removal. Furthermore, SINTEF Ocean has explored automation of land-based cultivation tanks to reduce manual labour and ensure consistent biomass quality.

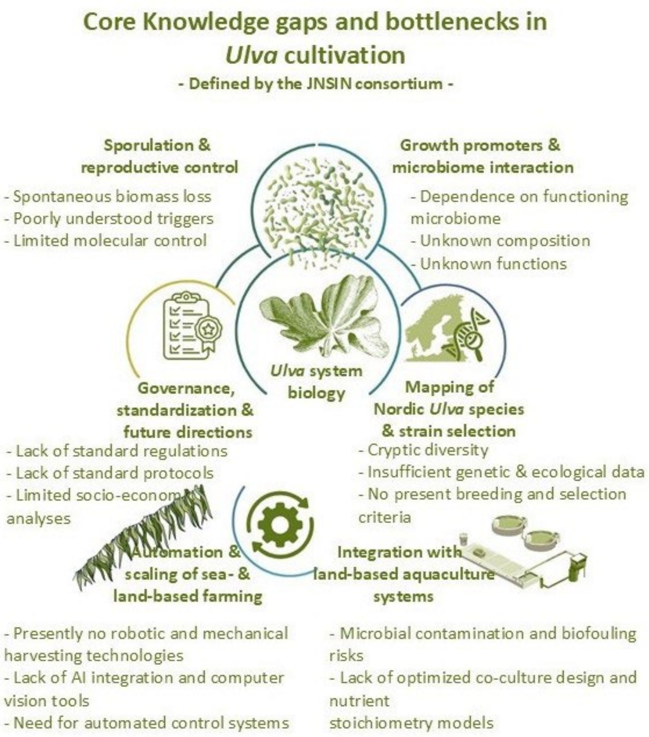
Cultivation in the rest of the Nordic countries are also increasing. In Finland, Åland, Iceland and The Faroe Islands there are already established seaweed farming companies. In Finland, the focus is on species tolerating the brackish conditions of the inner Baltic waters, including *Ulva* species, whereas the focus of the Atlantic Islands, Faroe Islands and Iceland, are more on the halophilic species such as kelps.

Knowledge gaps and bottlenecks

Despite the growing interest in *Ulva* cultivation as a sustainable source of biomass for food, feed, and biorefinery applications, several critical knowledge gaps and technical bottlenecks continue to constrain the development of large-scale, reliable production systems. Addressing these challenges is essential to secure year-round biomass supply, ensure environmental sustainability, and enhance the economic feasibility of *Ulva* aquaculture in the Nordic region. Some of the main knowledge gaps defined by the JNSIN consortium and workshop participants are presented below:

Sporulation and reproductive control

A fundamental bottleneck in *Ulva* cultivation lies in the limited understanding and control of its reproductive biology. Many *Ulva* species undergo spontaneous sporulation, leading to rapid degradation of the thallus and significant biomass losses in cultivation systems. The triggers of sporulation—such as nutrient limitation, light regime, temperature shifts, and hydrodynamic stress, and their interactions with internal sporulation and swarming inhibitors remain poorly characterized for Nordic species like *Ulva fenestrata* and *U. intestinalis*. Developing reliable methods for sporulation suppression or synchronized gametogenesis would enable predictable hatchery production and improve cultivation stability. Advances in molecular biology, including transcriptomic profiling of sporulation-related genes, may provide new insights into the regulatory mechanisms controlling reproduction.



Growth promoters and microbiome interactions

The role of the microbiome in *Ulva* growth and morphogenesis represents another major research frontier. Laboratory studies have shown that *Ulva* requires specific bacterial communities to develop normal morphology and to achieve optimal growth rates. However, the composition and functional roles of associated microbial consortia under Nordic conditions are still largely unknown. Understanding microbial interactions, particularly those influencing nutrient uptake, defense against pathogens, and production of growth-promoting metabolites, could lead to the development of probiotic or bioaugmentation strategies to enhance productivity. The integration of omics-based tools (metagenomics, metabolomics) with experimental cultivation trials is necessary to elucidate these complex symbiotic relationships and their ecosystem functions.

Mapping of Nordic Ulva species and their distribution

Accurate taxonomic and ecological mapping of *Ulva* species in the Nordic region remains incomplete. Molecular barcoding and population genetic analyses have revealed a high degree of cryptic diversity within the genus, complicating species identification and the selection of optimal strains for cultivation. Systematic mapping of *Ulva* populations across gradients of salinity, temperature, and nutrient availability is needed to identify strains with superior growth performance and environmental tolerance. Such baseline data are also crucial for monitoring potential ecological risks, such as genetic introgression between cultivated and wild populations or unintended range expansions.

Integration of Ulva cultivation with land-based aquaculture systems

Integrating *Ulva* production into land-based recirculating aquaculture systems (RAS) for fish or shellfish presents a promising pathway toward circular bioeconomy models. However, several technical and biological challenges remain. Optimizing nutrient uptake dynamics, maintaining stable water quality, and securing food/feed quality by preventing contamination by opportunistic microorganisms are key issues that require further investigation. Additionally, understanding the temporal variability of nutrient effluents from fish/shellfish farms is essential for designing efficient *Ulva* cultivation units that act as biofilters while producing valuable biomass. Research into co-culture system design, nutrient stoichiometry, and automated feedback control will be vital for successful implementation, while the legislative frameworks for utilizing *Ulva* produced though co-cultivation for food and feed need revision.

Automation and scaling of sea and land-based farming systems

Scaling up *Ulva* production in sea- and land-based systems is currently limited by high labour demands and variable process control, and in sea-based systems by costly harvest procedures which are not yet automated. Automation of hatchery management, biomass harvesting, and environmental monitoring represents an urgent technological need. The development of sensor-based control systems for parameters such as light intensity, dissolved CO_2, pH and nutrient levels, and biomass density could significantly enhance productivity and reproducibility. Moreover, integrating artificial intelligence and computer vision technologies to monitor *Ulva* morphology and detect early signs of stress or sporulation could further improve operational efficiency. Research collaboration between marine biologists, process engineers, and data scientists is required to advance these innovations.

Additional challenges and future directions

Beyond these key areas, other bottlenecks include the lack of standardized cultivation legislations and protocols adapted to Nordic environmental conditions, limited knowledge of seasonal variability in biochemical composition, and insufficient understanding of how large-scale *Ulva* farms interact with local ecosystems. Further, socio-economic studies assessing market potential, consumer acceptance, and policy frameworks are essential to support industrial expansion. At a national, Nordic and international level, authorities from the food, environmental and climate sectors need to align the regulatory frameworks in order to support the production of seaweeds, and specifically *Ulva*, as an industry simultaneously supporting both resource provision, environmental restoration and climate change mitigation. Coordinated efforts across academia, industry, and regulatory bodies, such as those facilitated by the JNSIN consortium, are crucial to overcome these barriers and establish a sustainable, knowledge-based *Ulva* aquaculture sector in the Nordic region.

Seaweed's role in the Nordic green transition

Within the JNSIN project we were able to validate, that sustainable seaweed cultivation presents a multifaceted opportunity for the Nordic region, contributing to environmental, economic, and societal objectives within the green transition emphasized also by the EU.

Beyond its commercial value, seaweed farming delivers significant ecosystem services. Cultivated seaweeds enhance nutrient cycling by absorbing nitrogen and phosphorus, potentially mitigating eutrophication in coastal waters and preventing nutrient emissions from land to sea, when cultivated in land-based systems. They potentially provide habitat for marine biodiversity, supporting fish and invertebrate populations, and can act as a natural buffer against ocean acidification and coastal erosion. These ecological functions position seaweed farming not only as a food or biomass production strategy but also as a potential tool for marine ecosystem restoration, offering measurable environmental co-benefits alongside economic returns. However, a robust Nordic seaweed industry has the potential to reinforce the blue economy by generating high-value products for food, feed, biofuels, pharmaceuticals, and bioplastics and other biomaterials. Seaweed's versatility, coupled with the Nordic region's technological expertise and favorable marine conditions, can foster innovation-driven industries, attract investment, and create employment in coastal communities – communities which have strongly suffered during the past century due to fish stock declines. Integration with other marine sectors, such as aquaculture and fisheries, may yield synergistic effects, enhance overall economic resilience and align with sustainable development goals. Furthermore, the expansion of seaweed production supports regional self-sufficiency in food, feed, and raw materials for biobased industries. By reducing dependency on imported plant-based proteins, fertilizers, and chemical inputs, seaweed can contribute to a circular bioeconomy that is resilient to global supply chain disruptions – which is particularly important given the vulnerabilities exposed by pandemics or geopolitical conflicts. Local production and processing infrastructure further reinforce strategic autonomy in the Nordic countries, while promoting sustainable consumption patterns.

Seaweed cultivation represents the intersection of environmental restoration, economic growth, and regional resilience. Its integration into Nordic strategies underlines its potential as a foundational component of the green Nordic transition, providing both environmental and socio-economic benefits.

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