



2026

**Developing a value hierarchy
for biomass: case study on kelp**

BELLONA REPORT

Address

Rue Breydel 42,
1040, Brussels, Belgium

Online

Email : europa@bellona.org
Website : eu.bellona.org

BELLONA

DISCLAIMER

Bellona endeavours to ensure that the information disclosed in this report is correct and free from copyrights but does not warrant or assume any legal liability or responsibility for the accuracy, completeness, interpretation or usefulness of the information which may result from the use of this report. © 2025 by the Bellona Foundation. All rights reserved. This copy is for personal, non-commercial use only. Users may download, print or copy extracts of content from this publication for their own and non-commercial use. No part of this work may be reproduced without quoting the Bellona Europa or the source used in this report. Commercial use of this publication requires prior consent of the Bellona Foundation.

Author:

Simon Hasselø Kline, Marine Biology Advisor

Co-Author:

Carolina Rodriguez Balda, Bioeconomy Policy Manager

Design and Editing:

Alissia Bourguignon, Communications Specialist

Rebecka Larsson, Senior Communications Manager



Co-funded by the European Union

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them



Table of Contents

Executive summary	4
1. Introduction: Beyond the Shoreline.....	5
2. The Biological Foundation.....	6
2.1 Kelp Physiology as an Industrial Advantage	6
2.2 The Harvesting Window and Perishability	6
3. The Logistical Bottleneck: From Sea to Factory.....	8
3.1 Stabilisation Strategies: drying vs ensiling.....	8
3.2 The Concept of Blue Ports	9
4. The Kelp Biorefinery: An Overview	10
4.1 Primary and Secondary Refining	10
4.2 Zero-Waste Engineering and Circular Utilities.....	10
4.3 Spatial Sensitivity: Protecting the Land to Save the Sea.....	11
5. Kelp Value Hierarchy.....	13
5.1 Tier 1: High-Value Bioactives	13
5.2 Tier 2: Functional Food and Health Ingredients	14
5.3 Tier 3: Agriculture and Functional Feed (The Methane Solution).....	14
5.4 Tier 4: Industrial Polymers and Textiles.....	15
5.5 Tier 5: Carbon Removal, CDR, and Bioenergy.....	15
6. Strategic Recommendations for the EU.....	17
7. Conclusion: An Innovative Marine-Based Biorefinery.....	18



Executive Summary

As the European Union (EU) intensifies its efforts to achieve climate neutrality by 2050, **the transition from a fossil-based economy to a circular bioeconomy has moved from a peripheral goal to a strategic necessity.** While the report on *Opportunities for increased Low-Trophic Aquaculture (LTA) in Europe: A two-part analysis of biomass availability and strategic opportunities in the EU/EEA* established the immense potential of LTA within European waters, this report shifts the focus to the critical post-harvesting phase. The central premise is that the scaling of LTA (especially kelp) will fail if it remains tethered to niche food markets. To unlock the multibillion-euro investments required for offshore expansion, **Europe must adopt a Biomass Value Hierarchy framework.**

This report argues that **the industrialisation of marine biomass requires a massive development of land-based infrastructure.** By viewing kelp as a versatile industrial feedstock rather than just a food product, biomass can be separated into high-value products, such as speciality biochemicals and functional animal feed. This biorefinery model ensures that every kilogram of harvested seaweed is utilised for its highest potential economic and ecological value. **The goal of this analysis is to provide the EU with a roadmap for transitioning away from petroleum-based precursors by leveraging the restorative capacity of marine biomass, both for ocean ecosystems and as a sustainable alternative to fossil-based resources.**

1. Introduction: Beyond the Shoreline

The report *Opportunities for Increased Low-Trophic Aquaculture in Europe* demonstrated that the European coastline, particularly the North Atlantic and the Baltic Sea, possesses a unique ecological advantage for the cultivation of macroalgae. It also established that the growth of LTA species is not only sustainable but restorative, acting as a nutrient sponge and a localised carbon sink. However, a significant gap remains between the biological success of a kelp farm and the commercial reality of a bio-industrial supply chain. Currently, the missing link in the European blue bioeconomy is the land-based infrastructure capable of receiving, stabilising, and refining millions of tonnes of kelp biomass.

The latest EU Bioeconomy Strategy (2025)¹ briefly recognises the potential of aquatic resources and the need to unlock under-used biomass. However, targeted actions and further innovation are still required to fully develop blue bioeconomy value chains. At the same time, the European Union's climate and nature goals will not be met without a robust, industrial-scale infrastructure for marine biomass processing. For kelp to displace petroleum-based products in the chemical, textile, and agricultural sectors, production needs to move beyond small-scale operations. Additionally, a Biomass Value Hierarchy should be defined, establishing a strategic ranking of biomass applications that prioritises high-value chemical extraction while providing the high-volume throughput necessary for industrial carbon removal, such as Bio-CCS or biochar.

The transition to this new bioeconomy requires the EU to view marine biomass not through the lens of traditional fisheries, but as a key industry to meet the climate goals of the 21st century. This report details the process of bringing that biomass onto land and the technological pathways required to refine it into a foundational pillar of European industrial autonomy.

¹ European Commission (2025). A Strategic Framework for a Competitive and Sustainable EU Bioeconomy. COM(2025) 960 final. Brussels.

2. The Biological Foundation

To understand the requirements for land-based refineries, one must first respect the unique physiology of kelp. Unlike terrestrial crops, kelp (predominantly *Saccharina latissima* and *Laminaria digitata* in European waters) grows with a speed and efficiency that few land plants can match. In optimal conditions, these species can increase their biomass between \approx 1-5 cm per day during the growth season.² This rapid growth is fuelled entirely by ambient sunlight and dissolved inorganic nutrients, requiring no arable land or freshwater.

2.1 Kelp Physiology as an Industrial Advantage

From an industrial perspective, kelp is essentially a high-performance bio-factory. Its tissue is rich in complex carbohydrates, notably alginates, laminarin, and fucoidans, which serve as the primary precursors for a wide array of industrial applications.³ Kelp also contains essential minerals and bioactive compounds that are highly concentrated compared to terrestrial alternatives.⁴ For a biorefinery, this means the raw material is pre-loaded with high-value chemicals. However, the high-water content, especially of brown algae, which can range between 80-90% of the total wet weight⁵, presents a significant logistical hurdle. Although the chemical composition of kelp can shift seasonally, storage carbohydrates such as laminarin and mannitol, structural polysaccharides like alginates, and minerals generally increase in summer and autumn as the tissues mature.⁶ Nutrient levels in the surrounding water can also dramatically impact biosynthesis and the chemical composition of kelp⁷, requiring the refining process to be as adaptive as the biology itself to maximise yield and product quality.

2.2 The Harvesting Window and Perishability

The biological cycle of kelp dictates a highly concentrated harvesting window. While the harvesting time varies according to species, in the North Atlantic harvesting typically occurs between April and June, before rising sea temperatures and biofouling (the growth of bryozoans or other organisms on the blades) degrade the quality of the biomass.⁸ This creates a surge of millions of tonnes of perishable material in a very short timeframe.

2 Sjøtun, K. (1993). Seasonal lamina growth in two age groups of *Laminaria saccharina* (L.) Lamour. in western Norway.

3 Xie, C., Lee, Z. J., Ye, S., Barrow, C. J., Dunshea, F. R., & Suleria, H. A. (2024). A review on seaweeds and seaweed-derived polysaccharides: Nutrition, chemistry, bioactivities, and applications. *Food Reviews International*, 40(5), 1312-1347.

4 Rupérez, P. (2002). Mineral content of edible marine seaweeds. *Food chemistry*, 79(1), 23-26.

5 Milledge, J. J., Smith, B., Dyer, P. W., & Harvey, P. (2014). Macroalgae-derived biofuel: a review of methods of energy extraction from seaweed biomass. *Energies*, 7(11), 7194-7222.

6 Schiener, P., Black, K. D., Stanley, M. S., & Green, D. H. (2015). The seasonal variation in the chemical composition of the kelp species *Laminaria digitata*, *Laminaria hyperborea*, *Saccharina latissima* and *Alaria esculenta*. *Journal of applied phycology*, 27(1), 363-373.

7 Juneja, A., Ceballos, R. M., & Murthy, G. S. (2013). Effects of environmental factors and nutrient availability on the biochemical composition of algae for biofuels production: a review. *Energies*, 6(9), 4607-4638.

8 Wilding, C., Tillin, H. M., Corrigan, S. E., Stuart, E., Ashton, I. A., Felstead, P., ... & Smale, D. A. (2021). Seaweed aquaculture and mechanical harvesting: an evidence review to support sustainable management.

Once removed from the sea, kelp begins to degrade almost immediately. Enzymes break down the complex sugars, and microbial activity can spoil the biomass within hours if it is not stabilised⁹. This biological reality defines the first requirement of the land-based value chain: stabilisation must occur at the point of landing. The design of the land-based infrastructure is therefore inseparable from the biological constraints of the plant. **If the EU is to process kelp at a scale that is necessary to move into a sustainable bioeconomy, the logistics of the “first mile”, from harvesting to stabilising, must be the priority of initial investment**

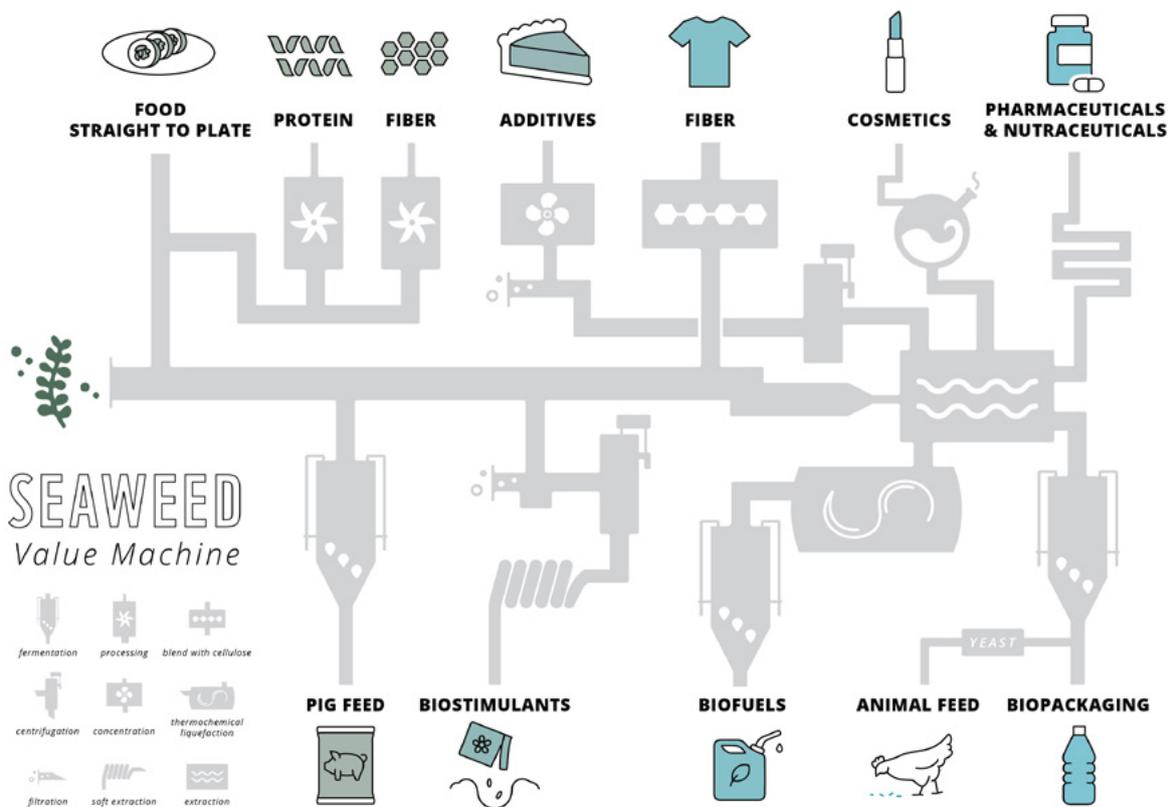


Figure 1: Seaweed production process (illustrative). The process and value chain for seaweed cultivation and uses resemble those for kelp described in this report. (Source: World Wildlife Fund).¹⁰

9 Vorse, J. G., Moody, C. T., Massoia, L. C., Perry, J. J., Burkholder, K. M., & Byron, C. J. (2023). Effect of post-harvest processing methods on the microbial safety of edible seaweed. *Journal of Applied Phycology*, 35(3), 1331-1346.

10 World Wildlife Fund, Farmed seaweed – sustainable seaweed aquaculture overview, accessed February 2026 <https://www.worldwildlife.org/our-work/oceans/sustainable-seafood/farmed-seafood/farmed-seaweed/>

3. The Logistical Bottleneck: From Sea to Factory

The primary obstacle to industrial-scale kelp utilisation is not the harvest itself, but the physics of moving a high-volume, low-density, and highly perishable material. The “wet” nature of kelp means that for every tonne of usable organic matter, a producer is essentially transporting multiple tonnes of water. As such, Europe should first solve the stabilisation and transportation puzzle through a combination of decentralised handling and centralised refining.

3.1 Stabilisation Strategies: Drying vs. Ensiling

To prevent spoilage and secure a year-round supply for refineries, biomass should be stabilised quickly after harvesting. Historically, the industry has relied on mechanical or natural drying. Although mechanical drying results in a stable, easily transportable product, it can be energy intensive. If this energy is derived from fossil sources, it can negate the carbon-sequestration benefits of the crop. Natural air drying, while requiring less energy than mechanical drying methods, is slow, needs more space around the harvesting area and often leads to unstable quality of the products¹¹.

A more industrial and energy-efficient alternative is ensiling, a lactic acid fermentation process similar to that used for terrestrial harvests¹². Ensiling allows wet biomass to be stored in large, airtight silos or bags, preserving the nutritional and chemical profile of the kelp for up to a year with minimal energy input. However, because the biomass remains wet, ensiling does not reduce volume or weight, meaning that significantly more mass needs to be transported to the processing facilities. Although ensiling may change certain biochemical properties of kelp biomass¹³, it can be a reliable method of preservation. In general, this method is best suited to decentralised or near-shore stabilisation and high-volume applications like animal feed and bio-fertilisers, as it is compatible with downstream liquid extraction processes.

¹¹ Lytou, A. E., Schoina, E., Liu, Y., Michalek, K., Stanley, M. S., Panagou, E. Z., & Nychas, G. J. E. (2021). Quality and safety assessment of edible seaweeds *Alaria esculenta* and *Saccharina latissima* cultivated in Scotland. *Foods*, 10(9), 2210.

¹² Larsen, S. U., Ma, N., Hou, X., Bruhn, A., Boderskov, T., MacLeod, A., ... & Bjerre, A. B. (2021). Ensiling of sugar kelp biomass for biorefining. *Biomass and Bioenergy*, 151, 106134.

¹³ Campbell, M., Ortuño, J., Ford, L., Davies, D. R., Koidis, A., Walsh, P. J., & Theodoridou, K. (2020). The effect of ensiling on the nutritional composition and fermentation characteristics of brown seaweeds as a ruminant feed ingredient. *Animals*, 10(6), 1019.

3.2 The Concept of Blue Ports

The EU should invest in Blue Ports. These ports are equipped with high capacity unloading systems and immediate primary stabilisation infrastructure, allowing wet biomass to be handled efficiently and safely. While elements of primary processing, such as chopping or ensiling, can already be performed during harvesting and are used in current operations, Blue Ports would enable these steps to be carried out in a more standardised, high-throughput, and logistically efficient manner. By co-locating stabilisation at the harbour, unnecessary transport of raw water can be minimised and the efficiency of the initial harvesting and downstream processing improved.

The EU should invest in the development of Blue Ports; which are specialised coastal hubs that serve as the interface between offshore farms and land-based biorefineries.



4. The Kelp Biorefinery: An Overview

The modern kelp biorefinery translates the principles of the Biomass Value Hierarchy into a tangible, operational system. Refining marine bioresources begins with the fractionation of kelp into its constituent components to produce platform chemicals, high-value molecules that serve as building blocks for a wide range of industrial products, alongside a range of co-products across multiple value tiers.¹⁴ Unlike traditional factories that produce a single output, kelp biorefineries are designed for cascading utilisation, systematically separating biomass into high-value bioactives, functional ingredients, feedstock, materials, and energy, ensuring that as little material as possible is lost to waste and that each fraction reaches its most valuable application.¹⁵

4.1 Primary and Secondary Refining

The process typically begins with mechanical pressing to separate the "kelp juice" from the solid pulp. The liquid fraction is rich in minerals and soluble sugars, making it a prime candidate for liquid bio-fertilisers or fermentation starters. The solid fraction, containing the structural carbohydrates such as alginate, can be routed into different secondary processing pathways within the biorefinery, including chemical refining for polymer extraction and enzymatic hydrolysis to produce substrates for downstream conversion.¹⁶

This cascading approach ensures that high-value compounds, such as speciality biochemicals are extracted first under gentle process conditions, while the remaining bulk material is processed in intensified large-scale industrial processes.¹⁷ By integrating multiple extraction lines into a single facility, the biorefinery achieves the economies of scope necessary to remain competitive with a petroleum-based chemical industry. This biorefinery model (see Figure 1) transforms kelp from a marine feedstock into a diverse stream of platform chemicals.

4.2 Zero-Waste Engineering and Circular Utilities

New biorefinery concepts should be designed to minimise waste streams and maximise the use of biomass by fostering carbon and energy efficiency optimisation. At industrial-scale, water recycling is not a secondary feature but a core operational requirement of a kelp biorefinery.¹⁸ The water brought in is filtered, treated via reverse osmosis (RO) to recover dissolved minerals and salts, and reused for the initial washing, cooling, and chemical ex-

¹⁴ Nilsson, A. E., Bergman, K., Barrio, L. P. G., Cabral, E. M., & Tiwari, B. K. (2022). Life cycle assessment of a seaweed-based biorefinery concept for production of food, materials, and energy. *Algal Research*, 65, 102725.

¹⁵ Herrera Barragán, J. A., Olivieri, G., Boboescu, I., Eppink, M., Wijffels, R., & Kazbar, A. (2022). Enzyme assisted extraction for seaweed multiproduct biorefinery: A techno-economic analysis. *Frontiers in Marine Science*, 9, 948086.

¹⁶ Blikra, M. J., Rode, T. M., Skåra, T., Maribu, I., Sund, R., Vaka, M. R., & Skipnes, D. (2024). Processing of sugar kelp: Effects on mass balance, nutrient composition, and color. *Lwt*, 203, 116402.

¹⁷ Kostas, E. T., White, D. A., & Cook, D. J. (2017). Development of a bio-refinery process for the production of speciality chemical, biofuel and bioactive compounds from *Laminaria digitata*. *Algal research*, 28, 211-219.

¹⁸ Zhang, X., & Thomsen, M. (2021). Techno-economic and environmental assessment of novel biorefinery designs for sequential extraction of high-value biomolecules from brown macroalgae *Laminaria digitata*, *Fucus vesiculosus*, and *Saccharina latissima*. *Algal Research*, 60, 102499.

traction phases. Advanced RO systems integrated into the facility ensure that freshwater consumption can remain near zero,¹⁹ a critical factor as climate change will continue to put pressure on freshwater availability. However, while water recycling significantly reduces freshwater demand, it requires energy for pumping, filtration, and RO; integrating renewable energy sources is therefore essential to maintain the carbon and energy efficiency of the facility.

The initial processing of the raw materials serves as the starting point for the following biorefinery process and are optimised for waste reduction. For example, the protein-rich residues from the alginate extraction line are diverted toward animal feed production, where they provide essential amino acids. The non-organic minerals that settle during processing are captured, dried, and returned to the fertiliser line as mineral concentrates.²⁰ The biorefinery process therefore has the capability of reducing its environmental footprint while lowering the production cost in the Biomass Value Hierarchy, ensuring that kelp-based products can eventually compete with their fossil-derived analogues.

4.3 Spatial Sensitivity: Protecting the Land to Save the Sea

A critical challenge in developing the necessary infrastructure for a successful bioeconomy is the risk of intensifying the nature crisis on land. The ongoing biodiversity crisis and massive habitat loss across Europe means that we cannot afford to displace intact terrestrial ecosystems or degrade coastal landscapes to build new bio-industrial facilities. Building a green industry that leads to nature degradation is a contradiction that undermines the very purpose of any bioeconomy.

The solution to the marine and climate crises must not involve the creation or exacerbation of a terrestrial one; if the goal of the Blue Bioeconomy is restorative, its physical footprint should be as ecologically invisible as possible.

The strategic solution is the intentional prioritisation of grey infrastructure²¹ and brownfield redevelopment.²² Europe's coastal regions are dotted with "grey areas" (e.g. abandoned shipyards, decommissioned oil and gas terminals, and abandoned power plants).²³ These sites may already possess the foundational requirements for marine kelp biorefineries: heavy-duty piers for vessel berthing, pre-existing energy grid connections, and established transport links to the mainland. By repurposing these degraded industrial sites, the EU can catalyse the blue bioeconomy without increasing the footprint on the land.

19 Zaky, A. S. (2021). Introducing a marine biorefinery system for the integrated production of biofuels, high-value-chemicals, and co-products: A path forward to a sustainable future. *Processes*, 9(10), 1841.

20 Torres, M. D., Kraan, S., & Domínguez, H. (2019). Seaweed biorefinery. *Reviews in Environmental Science and Bio/Technology*, 18(2), 335-388.

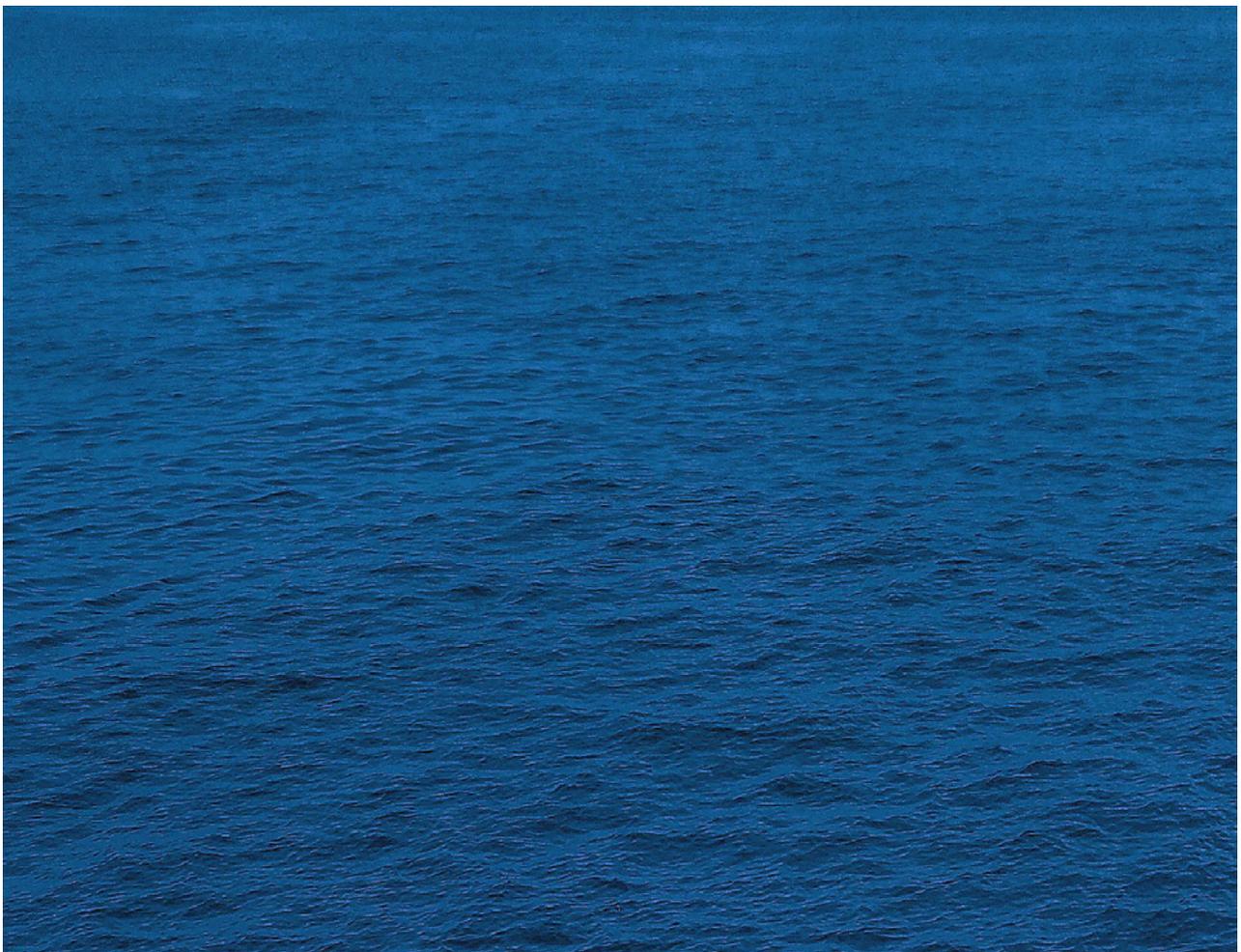
21 Singhvi, A., Luijendijk, A. P., & van Oudenhoven, A. P. (2022). The grey-green spectrum: A review of coastal protection interventions. *Journal of Environmental Management*, 311, 114824.

22 BenDor, T. K., Metcalf, S. S., & Paich, M. (2011). The dynamics of brownfield redevelopment. *Sustainability*, 3(6), 914-936.

23 Union, I. (2014). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Brussels. <http://www.w.xploit-eu.com/pdfs/Europe,202020,20>.

This Brownfield approach, which uses underutilised or vacant areas, ensures that the expansion of marine aquaculture remains a net-positive for Europe. It allows for the revitalisation of coastal communities that may have suffered from deindustrialisation while leaving terrestrial biodiversity such as forests, wetlands, and meadows untouched. Furthermore, utilising grey areas mitigates the "indirect land-use change" (ILUC) that often plagues bioenergy projects, where the demand for biomass can cause the degradation of natural habitats elsewhere.²⁴ It is therefore important to create a foundation for the bioeconomy where the LTA value chain ensures that economic scaling and nature conservation are not mutually exclusive, but synchronised.

The economic viability of the LTA sector relies on a tiered pricing strategy.²⁵ By extracting small amounts of high-value products first, the biorefinery can afford to produce bulk, low-cost commodities such as fertilisers. This approach follows the cascading use principle, ensuring that the harvested biomass contributes to diverse and sustainable products.²⁶



24 Daioglou, V., Woltjer, G., Strengers, B., Elbersen, B., Barberena Ibañez, G., Sánchez Gonzalez, D., ... & van Vuuren, D. P. (2020). Progress and barriers in understanding and preventing indirect landuse change. *Biofuels, Bioproducts and Biorefining*, 14(5), 924-934.

25 Rodrigues Dias, R., Deprá, M. C., Ragagnin de Menezes, C., Queiroz Zepka, L., & Jacob-Lopes, E. (2023). The high-value product, bio-waste, and eco-friendly energy as the tripod of the microalgae biorefinery: Connecting the dots. *Sustainability*, 15(15), 11494.

26 Lange, L., Bak, U. G., Hansen, S. C. B., Gregersen, O., Harmsen, P., Karlsson, E. N., ... & Hreggviðsson, G. Ó. (2020). Opportunities for seaweed biorefinery. In *Sustainable Seaweed Technologies* (pp. 3-31). Elsevier.

5. Kelp Value Hierarchy

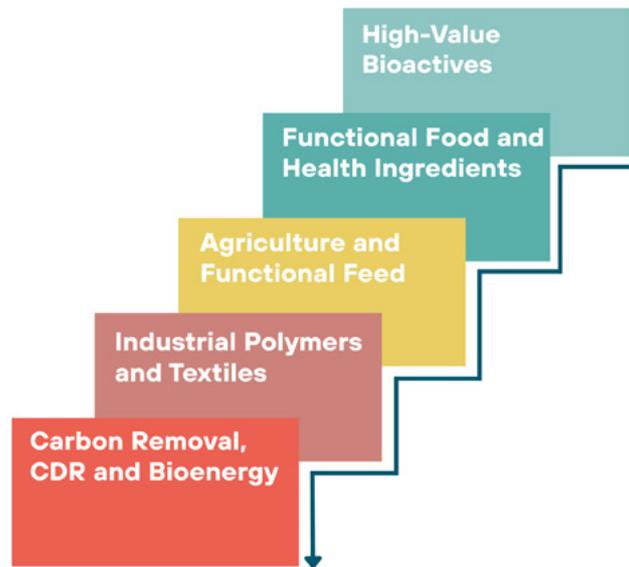


Figure 2: Bellona's proposed kelp value hierarchy

5.1 Tier 1: High-Value Bioactives

The apex of the hierarchy is occupied by bioactive molecules such as fucoidan and laminarin.²⁷ Fucoidan, a sulphated polysaccharide unique to brown seaweeds, has demonstrated significant potential in regenerative medicine, specifically in anti-thrombotic, anti-inflammatory, and anti-tumour applications²⁸ and can have high market-value.²⁹

The revenue generated from Tier 1 in an LTA-based biorefinery can in theory subsidise the higher-volume throughput required for the lower tiers.³⁰ It can provide the initial capital return that attracts the capital and energy needed to scale processing infrastructure and ensuring that marine biomass biorefineries are more than processing plants. Under the right regulatory and financial conditions these biorefineries can create high-skilled jobs within biotechnology and provide the EU with strategic autonomy in the production of critical pharmaceutical precursors.³¹

27 Herrera Barragán, J. A., Olivieri, G., Boboescu, I., Eppink, M., Wijffels, R., & Kazbar, A. (2022). Enzyme assisted extraction for seaweed multiproduct biorefinery: A techno-economic analysis. *Frontiers in Marine Science*, 9, 948086.

28 Flórez, N., Jesus Gonzalez-Munoz, M., Ribeiro, D., Fernandes, E., Dominguez, H., & Freitas, M. (2017). Algae polysaccharides' chemical characterization and their role in the inflammatory process. *Current Medicinal Chemistry*, 24(2), 149-175.

29 Bayu, A., & Handayani, T. (2018, December). High-value chemicals from marine macroalgae: opportunities and challenges for marine-based bioenergy development. In *IOP Conference Series: Earth and Environmental Science* (Vol. 209, No. 1, p. 012046). IOP Publishing.

30 Chew, K. W., Yap, J. Y., Show, P. L., Suan, N. H., Juan, J. C., Ling, T. C., ... & Chang, J. S. (2017). Microalgae biorefinery: high value products perspectives. *Bioresource technology*, 229, 53-62.

31 Zayed, A., & Ulber, R. (2019). Fucoidan production: Approval key challenges and opportunities. *Carbohydrate polymers*, 211, 289-297.

5.2 Tier 2: Functional Food and Health Ingredients

Beyond basic nutrition, kelp can provide functional benefits that address systemic health challenges in European populations. This includes prebiotic fibres that support gut microbiome health and iodine supplements.³²

In a European context where soil-depletion has led to mineral deficiencies in the human food chain, kelp-based supplements offer a bio-available solution to trace element malnutrition. Furthermore, kelp provides a sustainable source of Omega-3 fatty acids³³, bypassing the need for fish oil and reducing the pressure on wild forage fish stocks.

As the EU consumer base shifts toward plant-based organic products, the demand for kelp-derived thickeners (alginates) and natural preservatives internationally is expected to grow dramatically by the year 2030.³⁴

5.3 Tier 3: Agriculture and Functional Feed (The Methane Solution)

The application of macroalgae in livestock feed is perhaps the most immediate lever for climate mitigation available to the agricultural sector, addressing the EU greenhouse gas emissions derived from agriculture.³⁵ This potential is largely due to specific bioactives in kelp, which, when integrated into ruminant diets, interfere with the methanogenesis process in the rumen.³⁶ Pilot studies have shown that even a 1% inclusion rate of processed seaweed can reduce enteric methane emissions by as much as 67%,³⁷ representing a potential game-changer for the EU's Common Agricultural Policy (CAP) and its targets for non-CO₂ greenhouse gas reductions.

Beyond methane mitigation, kelp also enhances the strategic autonomy of European agriculture. Replacing imported soy and fishmeal with locally cultivated kelp proteins reduces the continent's imported deforestation footprint (particularly in the Amazon) and protects European farmers from global supply chain shocks and price volatility in global commodity markets,³⁸ concerns that have been further highlighted by the EU–Mercosur trade agreement, which will significantly liberalise agricultural trade with South American producers.³⁹

Additionally, by utilising kelp as a bio-stimulant, farmers can also reduce their reliance on synthetic nitrogen fertilisers⁴⁰, thereby lowering the carbon footprint of land-based food production.

32 Aoe, S., Yamanaka, C., Ohtoshi, H., Nakamura, F., & Fujiwara, S. (2021). Effects of daily kelp (*Laminaria japonica*) intake on body composition, serum lipid levels, and thyroid hormone levels in healthy Japanese adults: a randomized, double-blind study. *Marine drugs*, 19(7), 352.

33 Wang, Z., Scherbinek, M., & Skurk, T. (2026). Algae and Algal Protein in Human Nutrition: A Narrative Review of Health Outcomes from Clinical Studies. *Nutrients*, 18(2), 277.

34 Cai, J., Lovatelli, A., Aguilar-Manjarrez, J., Cornish, L., Dabbadie, L., Desrochers, A., ... & Yuan, X. (2021). Seaweeds and microalgae: An overview for unlocking their potential in global aquaculture development (FAO Fisheries and Aquaculture Circular No. 1229). Food and Agriculture Organization of the United Nations.

35 Silwer, H. (2018). Macroalgae as feed supplement for reduction of methane emission in livestock.

36 Altman, A., Vanzant, E., Davis, S., Harmon, D., & McLeod, K. R. (2024). Effects of a proprietary kelp blend product on enteric methane production and tissue residues in cattle. *Animals*, 14(16), 2411.

37 Roque, B. M., Salwen, J. K., Kinley, R., & Kebreab, E. (2019). Inclusion of *Asparagopsis armata* in lactating dairy cows' diet reduces enteric methane emission by over 50 percent. *Journal of Cleaner Production*, 234, 132-138.

38 Rauw, W. M., Gómez Izquierdo, E., Torres, O., García Gil, M., de Miguel Beascoechea, E., Rey Benayas, J. M., & Gomez-Raya, L. (2023). Future farming: Protein production for livestock feed in the EU. *Sustainable Earth Reviews*, 6(1), 3.

39 de Oliveira, S. E. C., Visentin, J. C., Pavani, B. F., Branco, P. D., de Maria, M., & Loyola, R. (2024). The European Union-Mercosur Free Trade Agreement as a tool for environmentally sustainable land use governance. *Environmental Science & Policy*, 161, 103875.

40 Singh, A., Sharma, K., Chahal, H. S., Kaur, H., & Hasanain, M. (2025). Seaweed-derived plant boosters: revolutionizing sustainable farming and soil health. *Frontiers in Soil Science*, 5, 1504045.

5.4 Tier 4: Industrial Polymers and Textiles

Replacing petroleum-based polymers with alginate-based fibres could contribute to decarbonising the consumer goods sector and addressing the impacts of the fashion industry, which is currently characterised by unsustainable production practices.⁴¹ Seaweed fibres can offer a regenerative alternative to the energy-intensive production of petroleum-based polyester and the water-intensive cultivation of conventional cotton.⁴²

However, realising this potential at scale will depend on the development of the infrastructure and the additional needed energy for these biorefineries and markets. Supplying the fashion industry would require the processing of large volumes of kelp with significant implications for energy use and logistics. As such, this tier represents a potential source of high-volume industrial offtake that could drive the demand for millions of tonnes of biomass and create a stable market for large-scale offshore farms. Its net climate benefits, however, should be demonstrated through robust life cycle and greenhouse gas performance assessments, benchmarked against existing textile production systems, as current small-scale production means the industry is still in its early stage.⁴³

5.5 Tier 5: Carbon Removal, CDR, and Bioenergy

The bottom of the hierarchy provides the climate foundation and ensures that the facility generates carbon removals. The residual fraction and extraction leftovers that cannot be utilised in higher tiers, can be processed through anaerobic digestion or pyrolysis, both of which operate in the absence of oxygen.⁴⁴

Anaerobic digestion is a process in which micro-organisms convert the organic fraction of the residues into biogas. Anaerobic digestion is a well-established technological process in wastewater treatment and sewage plants and is typically performed under liquid conditions on an industrial scale.⁴⁵ Given the potential high ash (inorganic) content of the residues and their moisture content at the end of the biorefinery process, anaerobic digestion could enable the cost-effective production of biogas from the digestate of the kelp.⁴⁶

Pyrolysis converts the carbon into a more stable form that is unlikely to undergo oxidation, namely biochar.⁴⁷ When applied to agricultural land, biochar can store carbon while improving soil water retention and aeration.⁴⁸

41 Badruddin, I. J., Silva, M. P., Tonon, T., Gomez, L. D., & Rahatekar, S. S. (2024). Modulating the properties of brown alga alginate-based fibers using natural cross-linkers for sustainable textile and fashion applications. *ACS omega*, 9(35), 37002-37011.

42 Vijayalakshmi, K., Latha, S., Rose, M. H., & Sudha, P. N. (2017). Industrial applications of alginate. In *Industrial applications of marine biopolymers* (pp. 545-575). CRC press.

43 Bao, H., Hong, Y., Yan, T., Xie, X., & Zeng, X. (2024). A systematic review of biodegradable materials in the textile and apparel industry. *The Journal of The Textile Institute*, 115(7), 1173-1192.

44 Deng, C., Lin, R., Kang, X., Wu, B., O'Shea, R., & Murphy, J. D. (2020). Improving gaseous biofuel yield from seaweed through a cascading circular bioenergy system integrating anaerobic digestion and pyrolysis. *Renewable and Sustainable Energy Reviews*, 128, 109895.

45 Van Haandel, A. C., & Lettinga, G. (1994). *Anaerobic sewage treatment*. John Wiley & Sons, London, England.

46 Border, A., Tolessa, A., Görgens, J., & Goosen, N. (2025). Anaerobic Digestion of Seaweed (*Ecklonia Maxima*) and Seaweed Residues for Quality Biogas Production. *Waste and Biomass Valorization*, 1-15.

47 Hung, C. M., Huang, C. P., Cheng, J. W., Chen, C. W., & Dong, C. D. (2021). Production and characterization of a high value-added seaweed-derived biochar: Optimization of pyrolysis conditions and evaluation for sediment treatment. *Journal of Analytical and Applied Pyrolysis*, 155, 105071.

48 Voruganti, C. (2023). Biochar applications in soil restoration: Enhancing soil health and carbon sequestration. *Environmental Reports*, 5(1), 1-4.

It can also be used as a soil amendment to improve soil health⁴⁹, such as in Southern Europe, where desertification is a growing threat. If the life cycle assessment of the feedstock used and the permanence of the stored carbon are properly accounted for, biochar could provide a Carbon Dioxide Removal (CDR)⁵⁰ and be recognised by the EU's Carbon Removal Certification Framework (CRCF). By valuing the carbon stored in the biochar, a secondary revenue stream can be created that is independent of commodity price fluctuations, providing a financial incentive for a potential biorefinery. In the future, it may be expected that industrial activities generate carbon removals within their value chains.

Moreover, the energy produced during final treatment (pyrolysis, anaerobic digestion) can be captured and used for the previous extraction processes. This could make the biorefinery a self-powering, potentially carbon-negative industrial hub, insulating it from the price volatility of the European natural gas market and helping the entire value chain achieve a net-negative carbon footprint.



49 Sharma, P., Ali, S., & Biswas, J. K. (2025). Application of biochar for soil erosion control and environmental management: implications for achieving sustainable development goals. *Discover Soil*, 2(1), 36.

50 Chiamonti, D., Lehmann, J., Berruti, F., Giudicianni, P., Sanei, H., & Masek, O. (2024). Biochar is a long-lived form of carbon removal, making evidence-based CDR projects possible. *Biochar*, 6(1), 81.

6. Strategic Recommendations for the EU



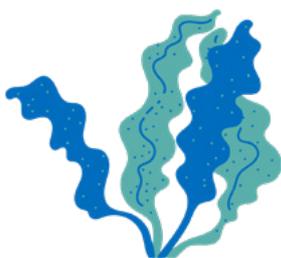
THE EU SHOULD ACT AS AN ARCHITECT & LEAD-INVESTOR OF THE NEW BIOECONOMY.

The transition to a marine-based industrial model requires the EU to act not just as a regulator, but as an architect and lead-investor of the new bioeconomy.



THE EU SHOULD IDENTIFY AND FAST-TRACK THE REDEVELOPMENT OF "GREY" COASTAL SITES FOR FUTURE BIOECONOMY POTENTIAL.

These clusters should be granted special economic zone status to attract private investment in biorefining, with streamlined permitting processes for facilities that utilise repurposed industrial land. This should include "Plug-and-Play" infrastructure where the state provides the primary utility connections and berthing rights.



THE EU SHOULD PROMOTE THE LARGE-SCALE ENSILING OF MARINE BIOMASS.

This ensures that biorefineries have a stable, year-round supply of feedstock, independent of the seasonal harvest window. Furthermore, the EU should implement "Contracts for Difference" (CfD) for bio-fertilisers to guarantee a minimum price for producers during the early years of market adoption.



7. Conclusion: An Innovative Marine-Based Biorefinery

The transition away from a petroleum-based economy is one of the defining challenges of our generation. Kelp offers a unique, restorative, and scalable source of hydrocarbons and nutrients that are currently extracted from fossil resources. However, **the potential of a marine-based bioeconomy can only be realised if the infrastructure required to handle its products and scale is put in place.**

By scaling production at sea and refining on existing "grey" industrial land, a restorative double benefit can be achieved. The health of the ocean can be restored through regenerative cultivation, while the integrity of terrestrial ecosystems can be preserved by avoiding development on greenfield sites.

The Biomass Value Hierarchy outlined in this report provides the economic framework to support this transition, converting marine biomass into the building blocks of a circular European bioeconomy. This represents a historic opportunity to shift Europe's industrial footprint sustainably towards the sea.

As this case study demonstrates, **marine biomass can provide viable non-fossil alternatives across sectors,** including chemicals and materials, food, and energy, actively displacing fossil fuels and accelerating the decarbonisation of the European economy. Based on this potential, **Bellona recommends that the EU establishes a clear Biomass Value Hierarchy, including waste and residues, grounded in the cascading principle.** Such a hierarchy is essential to guide decision-making when multiple sectors compete for the same bioresources, ensuring that biomass is allocated to the highest-value applications: prioritising food, feed, and materials over energy, while maximising energy and carbon efficiency and safeguarding climate, societal, and biodiversity objectives.

Without this prioritisation, biomass risks being diverted to low-value energy uses, undermining resource efficiency, climate goals, and ecosystem resilience. Implementing a politically supported hierarchy would translate the ambition of the EU Bioeconomy Strategy into actionable guidance, **making Europe's biological resources a driver of a sustainable, post-petroleum industrial system.**

References

- Altman, A., Vanzant, E., Davis, S., Harmon, D., & McLeod, K. R. (2024). Effects of a proprietary kelp blend product on enteric methane production and tissue residues in cattle. *Animals*, 14(16), 2411.
- Aoe, S., Yamanaka, C., Ohtoshi, H., Nakamura, F., & Fujiwara, S. (2021). Effects of daily kelp (*Laminaria japonica*) intake on body composition, serum lipid levels, and thyroid hormone levels in healthy Japanese adults: A randomized, double-blind study. *Marine Drugs*, 19(7), 352.
- Badruddin, I. J., Silva, M. P., Tonon, T., Gomez, L. D., & Rahatekar, S. S. (2024). Modulating the properties of brown alga alginate-based fibers using natural cross-linkers for sustainable textile and fashion applications. *ACS Omega*, 9(35), 37002–37011.
- Bao, H., Hong, Y., Yan, T., Xie, X., & Zeng, X. (2024). A systematic review of biodegradable materials in the textile and apparel industry. *The Journal of The Textile Institute*, 115(7), 1173–1192.
- Bayu, A., & Handayani, T. (2018). High-value chemicals from marine macroalgae: Opportunities and challenges for marine-based bioenergy development. *IOP Conference Series: Earth and Environmental Science*, 209(1), 012046.
- BenDor, T. K., Metcalf, S. S., & Paich, M. (2011). The dynamics of brownfield redevelopment. *Sustainability*, 3(6), 914–936.
- Blikra, M. J., Rode, T. M., Skåra, T., Maribu, I., Sund, R., Vaka, M. R., & Skipnes, D. (2024). Processing of sugar kelp: Effects on mass balance, nutrient composition, and color. *LWT*, 203, 116402.
- Border, A., Tolessa, A., Görgens, J., & Goosen, N. (2025). Anaerobic digestion of seaweed (*Ecklonia maxima*) and seaweed residues for quality biogas production. *Waste and Biomass Valorization*, 1–15.
- Cai, J., Lovatelli, A., Aguilar-Manjarrez, J., Cornish, L., Dabbadie, L., Desrochers, A., ... & Yuan, X. (2021). Seaweeds and microalgae: An overview for unlocking their potential in global aquaculture development (FAO Fisheries and Aquaculture Circular No. 1229). Food and Agriculture Organization of the United Nations.
- Campbell, M., Ortuño, J., Ford, L., Davies, D. R., Koidis, A., Walsh, P. J., & Theodoridou, K. (2020). The effect of ensiling on the nutritional composition and fermentation characteristics of brown seaweeds as a ruminant feed ingredient. *Animals*, 10(6), 1019.
- Chew, K. W., Yap, J. Y., Show, P. L., Suan, N. H., Juan, J. C., Ling, T. C., ... & Chang, J. S. (2017). Microalgae biorefinery: High value products perspectives. *Bioresource Technology*, 229, 53–62.
- Chiaromonti, D., Lehmann, J., Berruti, F., Giudicianni, P., Sanei, H., & Masek, O. (2024). Biochar is a long-lived form of carbon removal, making evidence-based CDR projects possible. *Biochar*, 6(1), 81.
- Daiglou, V., Woltjer, G., Strengers, B., Elbersen, B., Barberena Ibañez, G., Sánchez Gonzalez, D., ... & van Vuuren, D. P. (2020). Progress and barriers in understanding and preventing indirect land-use change. *Biofuels, Bioproducts and Biorefining*, 14(5), 924–934.

- de Oliveira, S. E. C., Visentin, J. C., Pavani, B. F., Branco, P. D., de Maria, M., & Loyola, R. (2024). The European Union-Mercosur Free Trade Agreement as a tool for environmentally sustainable land use governance. *Environmental Science & Policy*, 161, 103875.
- Deng, C., Lin, R., Kang, X., Wu, B., O'Shea, R., & Murphy, J. D. (2020). Improving gaseous biofuel yield from seaweed through a cascading circular bioenergy system integrating anaerobic digestion and pyrolysis. *Renewable and Sustainable Energy Reviews*, 128, 109895.
- European Commission. (2014). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: The urban dimension of EU policies – Key features of an EU urban agenda (COM/2014/0490 final). Brussels.
- European Commission. (2025). A strategic framework for a competitive and sustainable EU bioeconomy (COM(2025) 960 final).
- Flórez, N., Gonzalez-Munoz, M. J., Ribeiro, D., Fernandes, E., Dominguez, H., & Freitas, M. (2017). Algae polysaccharides' chemical characterization and their role in the inflammatory process. *Current Medicinal Chemistry*, 24(2), 149–175.
- Garcia, G., Soto, J., Valenzuela, C., Bernal, M., Barreto, J., Luzardo, M. D. L. C., ... & Cano, R. D. J. (2025). Gut microbiome modulation and health benefits of a novel fucoidan extract from *Saccharina latissima*: A double-blind, placebo-controlled trial. *Microorganisms*, 13(7), 1545.
- Herrera Barragán, J. A., Olivieri, G., Boboescu, I., Eppink, M., Wijffels, R., & Kazbar, A. (2022). Enzyme assisted extraction for seaweed multiproduct biorefinery: A techno-economic analysis. *Frontiers in Marine Science*, 9, 948086.
- Hung, C. M., Huang, C. P., Cheng, J. W., Chen, C. W., & Dong, C. D. (2021). Production and characterization of a high value-added seaweed-derived biochar: Optimization of pyrolysis conditions and evaluation for sediment treatment. *Journal of Analytical and Applied Pyrolysis*, 155, 105071.
- Juneja, A., Ceballos, R. M., & Murthy, G. S. (2013). Effects of environmental factors and nutrient availability on the biochemical composition of algae for biofuels production: A review. *Energies*, 6(9), 4607–4638.
- Khan, N., Sudhakar, K., & Mamat, R. (2024). Macroalgae farming for sustainable future: Navigating opportunities and driving innovation. *Heliyon*, 10(7), e28485.
- Kostas, E. T., White, D. A., & Cook, D. J. (2017). Development of a bio-refinery process for the production of speciality chemical, biofuel and bioactive compounds from *Laminaria digitata*. *Algal Research*, 28, 211–219.
- Lange, L., Bak, U. G., Hansen, S. C. B., Gregersen, O., Harmsen, P., Karlsson, E. N., ... & Hreggviðsson, G. Ó. (2020). Opportunities for seaweed biorefinery. In *Sustainable Seaweed Technologies* (pp. 3–31). Elsevier.
- Larsen, S. U., Ma, N., Hou, X., Bruhn, A., Boderskov, T., MacLeod, A., ... & Bjerre, A. B. (2021). Ensiling of sugar kelp biomass for biorefining. *Biomass and Bioenergy*, 151, 106134.
- Lytou, A. E., Schoina, E., Liu, Y., Michalek, K., Stanley, M. S., Panagou, E. Z., & Nychas, G. J. E. (2021). Quality and safety assessment of edible seaweeds *Alaria esculenta* and *Saccharina latissima* cultivated in Scotland. *Foods*, 10(9), 2210.
- Milledge, J. J., Smith, B., Dyer, P. W., & Harvey, P. (2014). Macroalgae-derived biofuel: A review of methods of energy extraction from seaweed biomass. *Energies*, 7(11), 7194–7222.

- Nilsson, A. E., Bergman, K., Barrio, L. P. G., Cabral, E. M., & Tiwari, B. K. (2022). Life cycle assessment of a seaweed-based biorefinery concept for production of food, materials, and energy. *Algal Research*, 65, 102725.
- Rauw, W. M., Gómez Izquierdo, E., Torres, O., García Gil, M., de Miguel Beascochea, E., Rey Benayas, J. M., & Gomez-Raya, L. (2023). Future farming: Protein production for livestock feed in the EU. *Sustainable Earth Reviews*, 6(1), 3.
- Rodrigues Dias, R., Deprá, M. C., Ragagnin de Menezes, C., Queiroz Zepka, L., & Jacob-Lopes, E. (2023). The high-value product, bio-waste, and eco-friendly energy as the tripod of the microalgae biorefinery: Connecting the dots. *Sustainability*, 15(15), 11494.
- Roque, B. M., Salwen, J. K., Kinley, R., & Kebreab, E. (2019). Inclusion of *Asparagopsis armata* in lactating dairy cows' diet reduces enteric methane emission by over 50 percent. *Journal of Cleaner Production*, 234, 132–138.
- Rupérez, P. (2002). Mineral content of edible marine seaweeds. *Food Chemistry*, 79(1), 23–26.
- Schiener, P., Black, K. D., Stanley, M. S., & Green, D. H. (2015). The seasonal variation in the chemical composition of the kelp species *Laminaria digitata*, *Laminaria hyperborea*, *Saccharina latissima* and *Alaria esculenta*. *Journal of Applied Phycology*, 27(1), 363–373.
- Sharma, P., Ali, S., & Biswas, J. K. (2025). Application of biochar for soil erosion control and environmental management: Implications for achieving sustainable development goals. *Discover Soil*, 2(1), 36.
- Singh, A., Sharma, K., Chahal, H. S., Kaur, H., & Hasanain, M. (2025). Seaweed-derived plant boosters: Revolutionizing sustainable farming and soil health. *Frontiers in Soil Science*, 5, 1504045.
- Singhvi, A., Luijendijk, A. P., & van Oudenhoven, A. P. (2022). The grey–green spectrum: A review of coastal protection interventions. *Journal of Environmental Management*, 311, 114824.
- Sjøtun, K. (1993). Seasonal lamina growth in two age groups of *Laminaria saccharina* (L.) Lamour. in western Norway. *Botanica Marina*, 36(5), 433–441.
- Torres, M. D., Kraan, S., & Domínguez, H. (2019). Seaweed biorefinery. *Reviews in Environmental Science and Bio/Technology*, 18(2), 335–388.
- Van Haandel, A. C., & Lettinga, G. (1994). *Anaerobic sewage treatment*. John Wiley & Sons.
- Vijayalakshmi, K., Latha, S., Rose, M. H., & Sudha, P. N. (2017). Industrial applications of alginate. In *Industrial Applications of Marine Biopolymers* (pp. 545–575). CRC Press.
- Vorse, J. G., Moody, C. T., Massoia, L. C., Perry, J. J., Burkholder, K. M., & Byron, C. J. (2023). Effect of post-harvest processing methods on the microbial safety of edible seaweed. *Journal of Applied Phycology*, 35(3), 1331–1346.
- Voruganti, C. (2023). Biochar applications in soil restoration: Enhancing soil health and carbon sequestration. *Environmental Reports*, 5(1), 1–4.
- Wang, Z., Scherbinek, M., & Skurk, T. (2026). Algae and algal protein in human nutrition: A narrative review of health outcomes from clinical studies. *Nutrients*, 18(2), 277.
- Wilding, C., Tillin, H. M., Corrigan, S. E., Stuart, E., Ashton, I. A., Felstead, P., ... & Smale, D. A. (2021). Seaweed aquaculture and mechanical harvesting: An evidence review to support sustainable management (Natural England Research Report NECR378). Natural England.

World Wildlife Fund. (n.d.). Farmed seaweed – sustainable seaweed aquaculture overview [Web page]. World Wildlife Fund, from <https://www.worldwildlife.org/our-work/oceans/sustainable-seafood/farmed-seafood/farmed-seaweed/>

Xie, C., Lee, Z. J., Ye, S., Barrow, C. J., Dunshea, F. R., & Suleria, H. A. (2024). A review on seaweeds and seaweed-derived polysaccharides: Nutrition, chemistry, bioactivities, and applications. *Food Reviews International*, 40(5), 1312–1347.

Zaky, A. S. (2021). Introducing a marine biorefinery system for the integrated production of biofuels, high-value-chemicals, and co-products: A path forward to a sustainable future. *Processes*, 9(10), 1841.

Zayed, A., & Ulber, R. (2019). Fucoidan production: Approval key challenges and opportunities. *Carbohydrate Polymers*, 211, 289–297.

Zhang, X., & Thomsen, M. (2021). Techno-economic and environmental assessment of novel biorefinery designs for sequential extraction of high-value biomolecules from brown macroalgae *Laminaria digitata*, *Fucus vesiculosus*, and *Saccharina latissima*. *Algal Research*, 60, 102499.



CONTACT

Simon Hasselø Kline
Marine Biology Advisor
Bellona

Phone

Mobile: +47 954 51 199

Online

Email: simon@bellona.no

Website: <https://bellona.no>

Bellona Europa is an international, independent and non-profit organisation that meets environmental and climate challenges head on. We are solutions-oriented and have a comprehensive and cross-sectoral approach to assess the economics, climate impacts and technical feasibility of necessary climate actions. To do this, we work with civil society, academia, governments, institutions, and industries.