

## **KELPONOMICS:**

### **A Comprehensive Analysis of the Global Seaweed Industry with Sustainable Strategies for Growth in the Icelandic Market**

*Prepared by*

**Emily Purcell**

**Juan Pablo Quintero**

*Client Partner*

**The Iceland Ocean Cluster**

**Alexandra Leeper, PhD**

**Clara Jégousse**

*Faculty Advisor*

**Dan Vermeer, PhD**

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Environment at Duke University*

## Executive Summary

Kelp and other types of seaweed are ecologically, culturally, and commercially valuable organisms which are garnering interest as the world looks for low-impact inputs to decarbonize heavy-emitting sectors and approach a net-zero carbon economy. Due to the rapid growth rate and minimal resource requirements of kelp and other varieties of brown macroalgae, researchers and companies are actively engaged in the advancement of the seaweed industry, seeking to uncover novel applications for this regenerative resource.

In addition to providing critical food, shelter, and habitat for biodiverse marine life, harvesting seaweed contributes to a \$9.9 billion global market encompassing a variety of end uses from puffed kelp chips to bioethanol and high-quality pharmaceutical alginates. Although the global seaweed industry is mature, growth, production, and usage are typically regional. Most of the supply and demand is centered in Asia (primarily in China, Japan, and Korea), and European markets are growing but relatively nascent.

We partnered with the Iceland Ocean Cluster to analyze the global seaweed industry and develop insights and recommendations for the Icelandic market. Through a systematic literature review and a series of expert interviews, we explored the commercial viability of various end uses for seaweed, their viability for the Icelandic market, and the ecological co-benefits provided.

### Key Findings:

- Seaweed has a high potential to decarbonize other sectors, most notably as a regenerative and sustainable farming source due to its high growth and low input characteristics.
- Ecosystem services offered by kelp and other seaweeds are promising solutions to convert the non-market value of ecosystem services to market value.
- Iceland has favorable geographic, economic, and political conditions to develop a seaweed industry that focuses on high-value and high-margin markets.
- Processing is the highest energy-use stage in a seaweed value chain, and Iceland is uniquely positioned to decarbonize this due to its high concentration of national geothermal energy.
- Barriers to growth in Iceland include the lack of a regulatory framework allowing ocean-based seaweed aquaculture and lack of access to financing.

### Principal Recommendations:

- Iceland should focus on high-value, high-margin seaweed products. The top 3 end-use markets we recommend for this market are hydrocolloids, biostimulants, and “other industries” where small-scale producers can innovate on high-value products.
- To remediate lack of regulatory framework, we proposed Iceland introduce a “National Seaweed Leadership Strategy” with policies designed to accelerate industry growth and develop the market sustainably.
- Innovation in valorization and circularity as another avenue to extract higher value from seaweed resources. Integrating seaweed aquaculture into existing supply chains can increase the country’s resilience and provide a steady local demand to grow the industry.

This comprehensive analysis underscores the immense potential of the global seaweed industry and presents strategies tailored specifically to facilitate sustainable growth within the Icelandic market, positioning stakeholders to capitalize on emerging opportunities and drive sustainable economic development while preserving the environment for future generations.

**“The number of living creatures of all Orders, whose existence intimately depends on the kelp is wonderful.”**

**– Charles Darwin, 1845 <sup>1</sup>**

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# Introduction

## Welcome to the Wonderful World of Kelp

The term “algae” encompasses a diverse group of organisms with wildly different physical characteristics, ecosystems, and functions. These can be broadly separated into microalgae (e.g., microscopic organisms such as plankton) and macroalgae which include some of the fastest-growing primary producers in the world such as the giant kelp *Macrocystis pyrifera*. Within macroalgae, three main divisions exist between red, brown, and green seaweeds. In this paper, we are limiting our scope to kelps and other species of brown algae due to common attributes, ecological roles, and commercial potential. We may refer to brown algae as kelp, seaweed, or simply algae in our analysis and will disambiguate red and green algae if relevant.



Figure 1: Shark in the Kelp Forest Source: oliver.dodd, Flickr.

There are over 100 kelp species of brown algae found in the cooler, shallower waters of the world, comprising the largest seaweeds and growing in dense and incredibly productive underwater forests (Figure 1).<sup>i</sup> <sup>ii</sup> In North America, they range from Baja California to Alaska on the West Coast and north of Maine in the East. South American kelp forests range from Peru down to Southern Chile and the Eastern Coast of Argentina. European kelps dominate the North Atlantic coasts from Scotland up through the Nordics and can also be found in warmer Mediterranean waters. Asia, where most seaweed aquaculture and human consumption

occurs, has its most productive ecosystems off the coasts of Japan, China, and Korea. African kelps can be found off the southern edge of the continent, and Oceanic kelps around Australia and New Zealand (See Figure 2). Kelp species construction can be complex and varied, with blades of various shapes and sizes, air filled bladders, strong holdfasts to anchor against heavy surf, or floating masses.<sup>iii</sup>

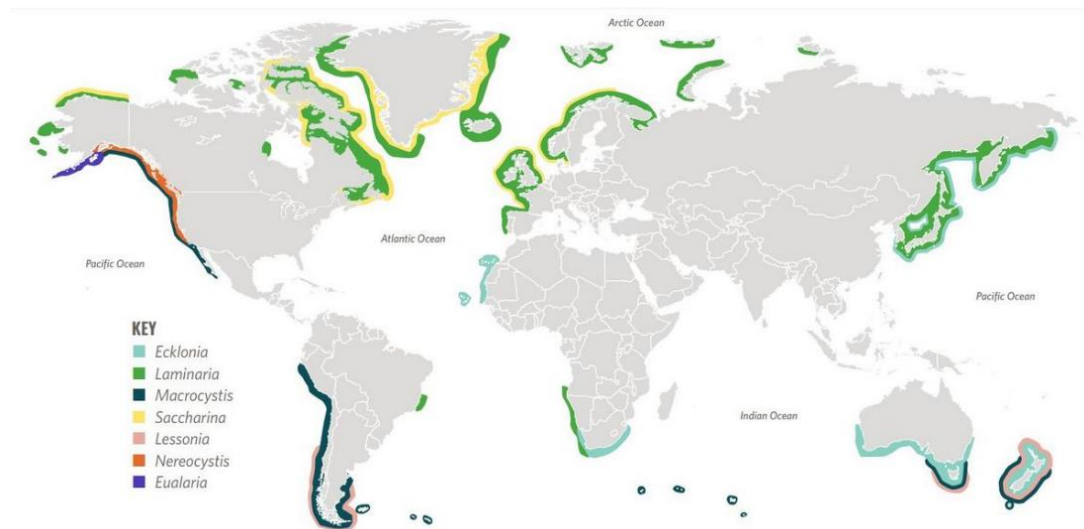


Figure 2: Global distribution of kelp. Source: Kelp Forest Alliance Guidebook 2022 <sup>iv</sup>

Kelp forests are biodiversity hotspots that have incredible value due to the ecosystem services they provide. Kelp are known as a keystone species, and are therefore critical to the health and resilience of other species in the ecosystem.<sup>v</sup> These vibrant underwater forests are akin to terrestrial rainforests, with thousands of species relying on them for shelter and use as spawning or nursery grounds.<sup>vi</sup> Their physical structures dissipate wave energy, reducing erosion and protecting coastal regions from flooding.<sup>vii</sup> Kelps also regulate the ocean's chemistry by absorbing phosphorus, nitrogen, and carbon as they grow, locally reducing eutrophication in nutrient-heavy waters.<sup>viii</sup> It is estimated that global seaweed stocks sequester 200 million tons of CO<sub>2</sub>, roughly equivalent to the annual emissions of South Korea.<sup>ix x</sup>

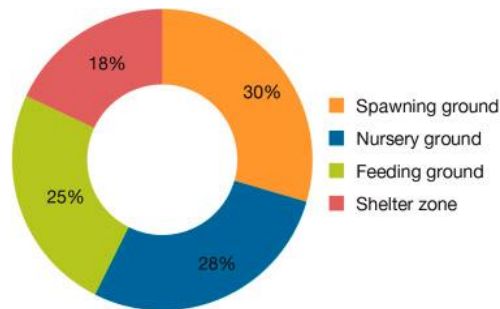


Figure 3: Ecosystem and social importance of seaweeds. Source: Hossain, Sharifuzzaman, et al, 2021

Humans have long recognized the value of this natural resource and harvested it for food and its many other uses. Although they are largely hidden under the surface these ecosystems are closer to us than we may think, with approximately 740 million people living within 50 km of a kelp forest.<sup>xi</sup> We spoke with experts from global environmental NGOs who educated us on the historical importance of seaweed when interviewed for this project. Seafaring Vikings ate kelp on long ocean voyages to prevent scurvy (a tradition lost due to cultural influence from Continental Europe); Japan has been cultivating seaweed for food as early as the 17<sup>th</sup> century; Europeans and Americans burned kelp and used the nutrient-rich ash for gunpowder in World War 1.<sup>xii xiii</sup>

Seaweed consumption remains most prevalent in Asia, which housed over 97% of global seaweed production in 2019, per the FAO.<sup>xiv</sup> While it may be little publicized in the Western world, seaweed is among the world's most grown crops, with estimates ranging between \$6-10 billion in revenues per year and more production by weight than lemons and limes.<sup>xv xvi</sup> In an interview with Fortune, a researcher from the WWF adds that seaweed is projected to surpass the potato as the fourth-most grown crop by 2051 if current growth rates hold (or sooner if they increase!)<sup>xvii</sup> While most seaweed is harvested for food use, there are many existing markets for its other uses. Hydrocolloids such as alginates and fucoidans from brown algae and carrageenan from red algae are used as biostimulants or additives in consumer goods, pharmaceuticals, and cosmetics. In Southern Chile, a species of bull kelp known locally as *cochayuyo* has been commonly consumed by Indigenous people for thousands of years. This staple can be used for soups, stews, baby food, and myriad other culinary uses. One of the authors sampled a kelp ceviche while traveling through South America and remarked that it was delicious.

Unfortunately, kelp forests, like many of the world's most valuable ecosystems, have been massively degraded due to human activity and anthropogenic climate change. A recent study found that 60 percent of the kelp forests have declined as of 2019, and are continuing to do so at an average rate of 1.8 percent per year.<sup>xviii xix</sup> Kelp communities in temperate latitudes are especially hard hit, with the severest rates of degradation found in regions close to the equator including Baja California, Western Australia, and southern New England.<sup>xx</sup> Due to the fact that kelps are keystone species in an ecosystem, trophic cascades of ecosystem collapse initiated by predator-prey dynamics, climate change-induced alterations in ocean temperature or chemistry, or anthropogenic disturbances like pollution or habitat destruction can have profound effects on kelp ecosystems. For example, a decline of sea otter predator species from overhunting and habitat degradation has led to an explosion of kelp-eaters such as urchins, which overgraze on the forests and prevent ecosystem regeneration, turning previously healthy ecosystems into barrens. Increased pollution and rising water temperatures have also reduced the resiliency of kelp

forests and changed geographic distribution as kelps move towards colder Northern waters. It is becoming harder and harder for kelp to thrive in the areas that need it most.

Against a background of ambitious climate goals set by countries and companies, we turn to kelp as a lower-impact source of food and biomass as well as a viable option for coastal community economic empowerment and resilience. Unlike other agricultural crops, kelp does not compete for land or fresh water, and does not require added fertilizer. Kelp grows fast and is restorative for ecosystems. With these built-in advantages, it is easy to see seaweed as a promising solution in the transition to a more sustainable world. We undertook this study to assess the economic and operational viability of different proposed uses for this resource, as well as the ecological services it contributes, to provide guidance for industry players in Iceland and around the world.

As we enter the decade of the ocean, it is once again time to recognize the incredible value of these wonderful organisms. We want to help the world to rediscover kelp.

## Iceland Background

### Iceland's Economy

Iceland has one of the fastest-growing economies in the OECD, and is centered around fishing, aluminum smelting, and foreign tourism.<sup>xxi</sup> Historically driven by fishing and fish processing, the country's blue economy remains a cornerstone, with fisheries contributing significantly to exports and employment. This comes as no surprise given that Iceland's productive waters rich in nutrients support biodiverse marine ecosystems teeming with life. In recent decades, Iceland has also developed a strong renewable energy sector, harnessing its abundant geothermal and hydropower resources to become a global leader in sustainable energy production.<sup>xxii</sup> Tourism has surged as another key economic driver, drawing visitors with its stunning landscapes, geothermal spas, and vibrant culture. Iceland has also seen growth in technology and innovation, with a burgeoning startup scene and a focus on green technologies in support of the country's ambitious climate target of reaching net zero before 2040.<sup>xxiii</sup> Despite its relatively small population, Iceland's economy stands as a testament to adaptability and sustainability, leveraging its unique natural resources and skilled workforce for continued growth and prosperity.

### Seaweed Harvesting in Iceland

Seaweed farming in Iceland has a history that stretches back centuries, with early records indicating its use in food, agriculture and medicine by the Norse settlers. However, it wasn't until the mid-20th century that commercial seaweed farming began to take shape. In the 1970s, efforts to cultivate seaweed for industrial applications began with a focus on species like kelp for alginate production. Currently, Iceland's seaweed industry is based solely on wild cultivation with around 15 companies and startups sourcing seaweed for their products and research.<sup>xxiv</sup> Iceland's longest established seaweed production and processing company, Thorverk located in the Westfjords, harvests wild seaweed from Breiðafjörður to produce

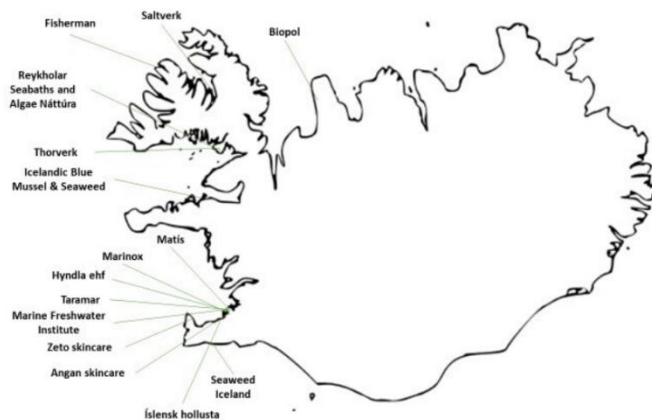


Figure 4: Seaweed company locations in Iceland. Not shown, Running Tide. Source IOC.

geothermally dried and milled seaweed that is used for fertilizer, animal feed, cosmetics, and pharmaceutical products.<sup>xxv</sup>

Iceland's small but established seaweed industry presents significant opportunities for growth, industry diversification and resilience. While there remains capacity in wild harvest stocks, expanding a seaweed economy sustainably will require aquaculture. Large-scale aquaculture projects are already underway in land-based and microalgae farming which has grown considerably over the last ten years, and interest is growing in offshore macroalgae farming. Icelandic legislation is in place for wild harvest operations with an annual cap on biostock removals, but macroalgae aquaculture currently lacks regulation in Iceland to allow for commercial cultivation. However, there is increasing investment in aquaculture research and experimentation with three main companies experimenting with seaweed cultivation: Hyndla is experimenting with growing red algae in tanks on land for the food supplement and pharmaceutical industry, and Nordic Kelp and Eldey Aqua are piloting marine cultivation lines.<sup>xxvi</sup>

Given the potential for growth and the government's stated plans to develop a comprehensive aquaculture policy, seaweed aquaculture has the potential to become a new pillar for the Icelandic economy.<sup>xxvii</sup> Regulations will be needed to scale these operations, and in the meantime, Iceland continues to support innovation and research to explore seaweed farming initiatives with a growing emphasis on new sustainable industries.

## The Iceland Ocean Cluster

Our research partner, the Iceland Ocean Cluster (IOC), is a dynamic innovation hub and network connector at the forefront of Iceland's blue economy, uniting diverse sectors of industry, academia, innovation and entrepreneurial, and marine industry to foster collaboration and sustainable growth in the blue economy. Situated in Reykjavik, IOC serves as a catalyst for entrepreneurship, research, and development of value creation from blue biomasses in Iceland and around the world. By bringing together businesses, academia, and government agencies, the IOC creates a productive environment for cross-sectoral innovation through its initiatives such as networking events, incubation programs, and knowledge-sharing platforms.

Notably, the IOC established a model for the full utilization and optimized value creation from Atlantic cod through their core program called "100% Fish". The IOC has a strong focus on innovation and collaboration both domestically and internationally, and is involved in national, Nordic, European, and International research and innovation grants and consultancy projects that focus on both the blue and circular economy. This work aided by the international network of sister Ocean Clusters that seek opportunities to collaborate for sustainable blue value creation and knowledge transfer and include Ocean Clusters in the United States, The Pacific Islands, Namibia, Denmark, and the Faroe Islands. With a strong focus on sustainability and economic viability, the Iceland Ocean Cluster plays a pivotal role in advancing Iceland's position as a global leader in the blue economy and facilitating globally.

Traditionally, the Icelandic blue economy has been predominantly shaped by fisheries, contributing significantly to the country's economic growth. However, there exists an opportune moment to diversify this growth trajectory by extending focus towards other interconnected sectors. Particularly, high-potential value chains such as aquaculture and algae have garnered attention as promising areas for future development. This research endeavor, conducted in collaboration with the Icelandic Ocean Cluster (IOC), aims to provide a thorough examination of seaweed as one such potentially viable sector within the broader framework of economic expansion and sustainability initiatives. We would like to extend an emphatic thank you to Dr. Alexandra Leeper, Managing Director, and Clara Jégousse, Research

Specialist at the Iceland Ocean Cluster for their work with us together on this research project for the last 8 months. Their specialized knowledge innovating ocean sectors and extensive networks in Iceland and beyond enabled their support of our research process, expansion of our expert interview portfolio, and guidance of our literature review process.

**Case Study 1. Aquatic Innovations: The Success of Iceland Ocean Cluster's Core '100% Fish' Program**

"100% Fish" has supported the optimized value creation and utilization of more than 90% of cod by bringing together stakeholders from the traditional fisheries and processing sector with researchers from the food, feed, cosmetic, fashion and medical sectors. The program has given rise to Iceland's first Unicorn, created new companies and jobs for rural communities and led to a single fish increasing in total value from \$12 to almost \$5000. IOC now aims to adapt the 100% fish model to other blue bio-based resources, to reduce waste and create blue economy value. In Iceland, this program has gained worldwide recognition for facilitating the utilization of approximately 90% of Atlantic cod from Icelandic fisheries, supporting the transformation of a single cod from a value typically ranging from a dozen to hundreds of dollars, potentially reaching thousands of dollars. This shift occurs as different parts of the fish, once considered waste, are developed into successful market products ranging from lower-value items like feed to higher-value products like nutraceuticals, textiles, and medical products. The program is now applying the Icelandic "100% Fish" framework to seafood around the world.

## Project Overview

### Research Question

While the ecological and economic benefits of kelp seem well established, we wanted to take these assumptions several steps further and investigate both the global and local Icelandic seaweed market.

***Research Question 1: What does the global seaweed market look like and what are key trends to consider?***

We first took a macro view of seaweed markets through an extensive literature review and accompanying key expert interviews. This exploration sought to provide a basis of understanding of the drivers, trends, and challenges of the current global seaweed market to be further distilled in the next research iterations.

***Research Question 2: What are Iceland's key advantages and disadvantages when it comes to developing their kelp market and what recommendations can inform public and private stakeholders?***

For the second phase of our research, we focused on one specific type of seaweed (brown algae/kelp) and one specific market (Iceland). Using the research that we gathered in the first phase, we pursued specific leads for Iceland kelp markets to validate assumptions and further understand the local market drivers through more targeted desk research and 17 primary interviews.

***Research Question 3: How can we present ecological value to stakeholders and ensure that sustainability is accounted for in the decision-making process?***

In addition to the market drivers explored in our first two research questions, we also conducted research into the ecological benefits and values of kelp and analyzed how these line up with the markets we identified.

### Deliverable Outputs:

- Completed literature review
- 17 completed interviews with global seaweed experts
- Market analysis of kelp industry
- Kelp value chain map (see Figure 6)
- Potential kelp aquaculture sites (see Figure 9)
- Final recommendations for Iceland

## Methodology

The purpose of our research plan was to gain a strong basis of understanding of kelp ecosystems, markets, economics, and technologies and to ensure that our research review was systematic, comprehensive, and replicable. We included both secondary sources from peer-reviewed scientific papers and industry-relevant webpages and publications to capture a comprehensive view of the subject, and validated these sources with primary industry expert interviews.

Our approach consists of:

- Systematic Literature Review
- Expert Interviews
- Geospatial Mapping

We examined market and non-market value separately with more detail in their respective sections.

## Literature Review

Our team conducted systematic literature review using Boolean search terms reviewed with Duke University Science Librarian faculty. Our review explored the economic and environmental impact potential of kelp in and around Iceland. We conducted this literature search targeting 3 key electronic databases: Web of Science (WoS) and Environment Complete (EBSCO) to source peer-reviewed articles published in academic journals, and Earth, Atmospheric & Aquatic Sciences Collection (ProQuest) to encompass grey literature (non-peer reviewed sources). Our search criteria included papers published within the last five years in English. Our full Boolean search log and keywords can be found in the appendix.

Our initial search pulled an initial 157 articles from peer-reviewed journals and grey literature. We conducted two rounds of screening to narrow down our review articles (see Figure 5). The first screening reviewed the title, abstract, and year published for each article pulled from the target databases to determine appropriate fit for our research question, narrowing down to 85 articles. The second screening further focused our list of articles to 48 as we conducted a full review of each paper.

Additional publications were identified through back-and-forth sourcing of citations, desk research, and recommendations from our expert interviewees that supplemented our literature review. Following the final screening of papers, our team manually extracted information from the selected articles and validated it through our key expert interviews for further synthesis.

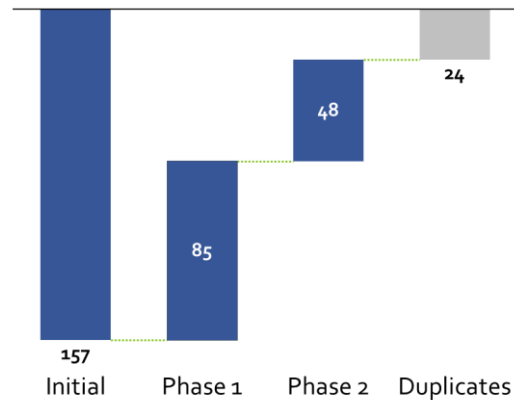


Figure 5: Literature Review Selection Process. Source: Team Analysis

## Expert Interviews

We targeted experts across the global and localized seaweed-focused organizations for our primary research. We interviewed 17 experts across regions and across stakeholder groups. Table 1 below outlines a summary of the interviews we conducted.

Some of our interviewees asked us not to publish their identity and organization, so we have kept them anonymous.

Category	Number of Interviews	Organizations
Research and Education Institutions	4	<ul style="list-style-type: none"> <li>• KTH Royal Institute of Technology</li> <li>• Nicholas Institute</li> <li>• Nicholas School of the Environment</li> </ul>
Industry Associations/Coalitions	5	<ul style="list-style-type: none"> <li>• Lava Seaweed (CircleFeed Project)</li> <li>• Association of Algae Iceland</li> <li>• Kelp Forest Alliance</li> <li>• Pacific Seaweed Industry Association</li> <li>• Global Seaweed Coalition</li> </ul>
Nonprofit Organizations	1	<ul style="list-style-type: none"> <li>• <i>International NGO 1 [Anonymized]</i></li> </ul>
Blue Tech Accelerator/Startups	3	<ul style="list-style-type: none"> <li>• Urchinomics</li> <li>• Running Tide</li> <li>• Transition Labs Iceland</li> </ul>
Kelp Cultivators & Processors	2	<ul style="list-style-type: none"> <li>• Pacific Kelp Co.</li> <li>• ÍslandPari</li> </ul>
Food & Beverage Corporations	2	<ul style="list-style-type: none"> <li>• <i>International Pet Care Company 1 [Anonymized]</i></li> </ul>

**Regions covered:** US (Maine, Alaska), Canada (British Columbia), Iceland, Sweden, Australia, and broad Europe/Global-focused organizations. About 30 percent of the organizations represented are based out of Nordic countries.

While we were able to interview 1 industrial buyer, a future stage of this research would benefit from interviewing buyers across each economic segment covered in this paper (e.g., companies purchasing blue carbon credits, retailers selling seaweed-based foods, pharmaceutical/nutraceutical companies). A key barrier we found was getting market information on costs, purchase price, and margins for raw and processed kelp, which is proprietary to each organization and varies across species, region, and end use. Having access to this data would facilitate completing a more robust economic analysis.

Future research would also benefit from primary interviews with policymakers focusing on aquaculture and oceans in Iceland and other regions with active seaweed industries. A recurring theme for growth in the kelp cultivation sector is the importance of a well-defined and well-resourced regulatory process that enables rather than blocks the development and scaling of aquaculture operations. Better understanding the strategic priorities for governments, the process of creating algae-focused policy, avenues to access government financing, and the timelines for policy implementation would help guide communication between public and private sector actors and develop a roadmap for a sustainable seaweed industry.

## Geospatial Analysis of Aquaculture Sites

We conducted a geospatial analysis of potential project sites for kelp aquaculture in Iceland. This included identifying key environmental characteristics of kelp habitat, such as temperature, pH, and nutrient range requirements, and analyzing potential sites based off of these characteristics within the 200 nautical-mile Iceland Exclusive Economic Zone (EEZ). Please refer to Figure 9 in the Results and Discussion section to review the final map.

## Results and Discussion

### Global Market Insights

The burgeoning global interest in kelp, fueled by its multifaceted applications and environmental benefits, underscores its pivotal role in shaping the future of various industries and ecosystems.

Our research illuminated several key global seaweed market insights:



**Seaweed can help decarbonize other sectors:** Seaweed, particularly kelp, has emerged as a transformative agent in the fight against climate change, offering innovative solutions to decarbonize sectors including food, energy and plastics materials, regenerative fisheries and farming product.



**High potential as a sustainable farming source:** Kelp's rapid growth rate, minimal resource requirements, and ability to absorb excess nutrients position it as a promising candidate for sustainable farming practices on a global scale, offering a solution to meet the increasing demand for food and biomass while mitigating environmental degradation.



**Global seaweed markets are massive and growing:** With a global market size of \$9.9B, the demand for seaweed-derived products surges driven by its nutritional value and versatility. Global seaweed markets witness exponential growth – seaweed will outpace potatoes as one of the world's most grown crops by 2050 – presenting lucrative opportunities for stakeholders across industries.<sup>xxviii</sup>



**Ecosystem services other than carbon credits to be explored:** Seaweed blue carbon credits remain nascent, but other ecosystem services such as nitrogen credits have shown success in localized pilots. Beyond carbon credits, kelp offers a myriad of ecosystem services yet to be fully explored, further amplifying its significance in both environmental and economic landscapes.

## Kelp Value Chain

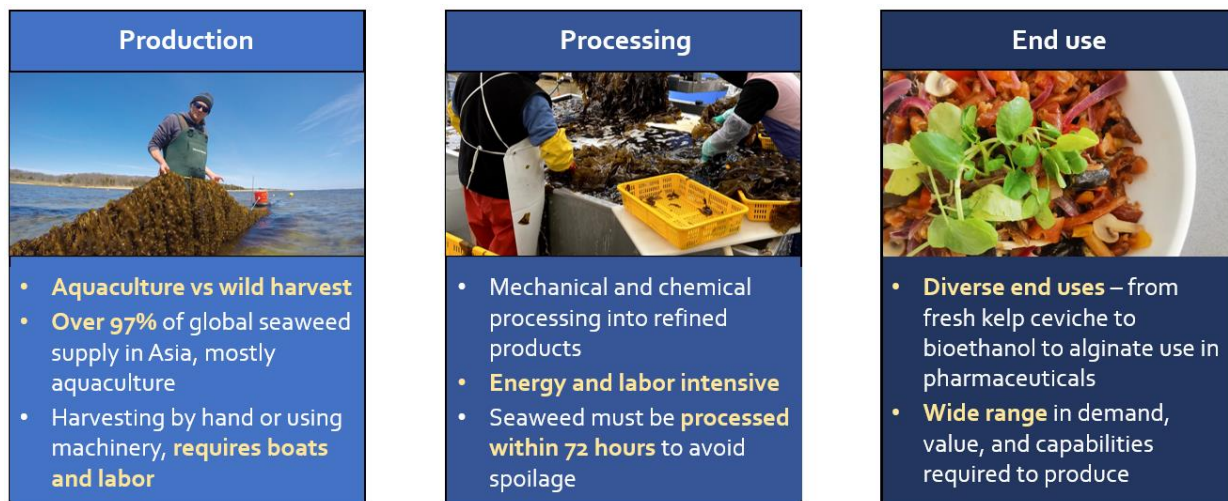


Figure 6: Kelp Value Chain. Source: Researcher analysis.

The kelp value chain can be segmented broadly into three phases – production, processing, and end-use. In our research, we have seen companies that operate across one, two, or all three. Typically, vertically integrated companies can capture more value, as they control their supply and can sell higher-value branded products.

### Production

Globally, over 97% of global seaweed is cultivated in mass operations, mainly in Asia. Seaweed can be farmed in near-shore environments reliably, and most species can be harvested multiple times per year. Aquaculture operations range from small-scale growers, who may be fishermen looking for additional income streams to industrial operations. Cultivated algae account for nearly 30% of world aquaculture and over 50% of global mariculture (aquaculture in salt water).<sup>xxix xxx</sup>

Kelp is typically grown close to shore, where plants are grown on seeded ropes and harvested when mature. There is potential for offshore aquaculture in deeper waters, but it is riskier and more expensive due to additional operational complexity. Harvesting is typically done by hand, or using tools and boats, depending on species, intended use, and scale of operation. One of our industry experts adds that in some areas, including Iceland, harvesting is seasonal due to harsh weather conditions in winter.<sup>xxxii</sup> Emissions from production typically include operation of hatcheries, embedded emissions from equipment, and fuel for vessels used for collection.

Wild harvest can only produce small volumes sustainably, as overharvesting can be harmful to biomes and even lead to ecosystem collapse. Sustainable wild harvest operations will typically cut the algae above the holdfast, and will rotate harvest locations, leaving harvested fields untouched for 4 to 5 years for stocks to regrow. Sustainable wild harvest can be positive for ecosystems, as younger algae can grow faster once the mature plants have been harvested.<sup>xxxii</sup> Production in Europe (including Iceland), representing less than 1% of global macroalgae production, is primarily through wild harvest.

In our research, we have seen companies have success with owned and operated farms, as well a hub-and-spoke model where they contract many small farmers to grow and harvest seaweed and ship to a central location for processing.

In many countries, seaweed cultivation is primarily done by women and indigenous communities, creating valuable revenue streams for traditionally marginalized groups.

## Processing

Fresh seaweed has a short shelf life and must be processed or consumed within 2-3 days of harvest before it spoils. Processing can range in complexity from drying and milling the seaweed to a full biorefinery process where different components are separated into higher-value compounds. Processing typically requires high energy inputs and can frequently be the most carbon-intensive part of the value chain outside of geothermal- and solar-powered processes. Biorefinery processing can also necessitate special enzymes or chemicals for treatment, which increase the environmental footprint.

Because processing must be done close to the production location, these operations create jobs for local coastal communities. One of our experts interviewed from Icelandic producer Íslandsþari informed us that they had ~10x more employees working in processing than production. <sup>xxxiv</sup>

Processing companies typically create intermediate products, such as dry kelp powder, alginates, or liquid kelp extract which are sold to bigger buyers as inputs for their operations. Our interviewee from Íslandsþari commented that kelp can have up to 13 marketable components. <sup>xxxv</sup> Sophisticated processors can produce multiple streams of revenue and get higher value for their seaweed.

## End-Use

Kelp has many uses ranging from nutrition, agriculture, bioenergy and more. Players in the end use part of the value chain can range from a local organic restaurant offering fresh kelp, to a small vertically integrated producer selling kelp-based cosmetics, to a global chemicals company selling millions of dollars' worth of hydrocolloids to industrial customers.

We summarize research for each major identified end markets in “Market Value” section of the paper. A brief visualization of the different end markets can be found in Figure 7.



Figure 7: 100% Kelp Wheel, Source: Iceland Ocean Cluster

## Trends in Value Chain

A common theme in our expert interviews is that the market outside of Asia is nascent and is facing a “chicken-or-and-egg” scenario where end-use players find it difficult to secure reliable supply, and growers find it difficult to secure reliable buyers. <sup>xxxvi</sup> In one our interview with a seaweed researcher from the KTH Institute of Technology in Sweden, we learned that most sector investment goes into developing end products and not feedstock production, which only gets ~15% of industry funding. <sup>xxxvii</sup>

Another expert we interviewed from Canadian producer Pacific Seaweed added that venture capitalists have expressed interest in the space but are not funding kelp companies due to concerns over lack of data and no straightforward paths to market. <sup>xxxviii</sup> He adds that until the seaweed industry hits a critical mass that drives price to the “tipping point” where it can be profitable at scale, it will be difficult to unlock the industry’s potential.

A common theme in our interviews is that there is tremendous interest and potential to develop seaweed into a major industry in Europe and North America due to its unique properties and value as a low-impact feedstock. Increasing access to finance, a clear regulatory framework, and government support can reduce risk and create friendlier conditions for the industry to grow.

## Iceland's Unique Attributes

High-yield and value kelp species such as *Laminaria* and *Saccharina latissimi* grow well in Iceland's cold waters, which has an estimated area of 10,771 km<sup>2</sup> of macroalgae growing in its arable waters.<sup>xxxix</sup>

Iceland kelp forests are found on shallow rocky coastlines up to 30 meters in depth and are comprised of rockweed *Ascophyllum nodosum* (knotted wrack), several species of the genus *Fucus*<sup>1</sup>, *Laminaria digitata* (Oarweed), *Laminaria hyperborea* (tangle) in the northern fjords, and *Saccharina latissimi* (sea belt or sugar kelp) in brackish fjords.

There is rising global interest in growing and processing seaweed as well as for a variety of end products.<sup>xi</sup> Macroalgae sales from Iceland producers in 2020 totaled €15.5M and are expected to grow considerably over the next 10 years with sector advancements in technology, processing, and algae aquaculture potential.<sup>xii</sup> Iceland broadly has ideal ecologic and economic conditions for a prosperous seaweed industry but is hampered by a lack of regulatory framework as well as a lack of a market of producers and buyers at scale.

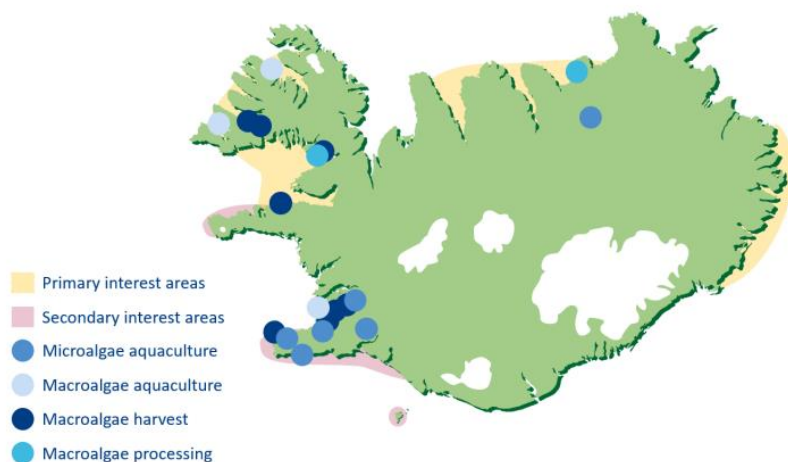


Figure 8: Map of existing micro- and macroalgae facilities and potential cultivation areas in Iceland. Source: Government of Iceland.

## Iceland Differentiators

Although the current Icelandic kelp market is small in scale compared to other markets, especially in Asia, differentiating factors make Iceland an attractive market for expansion.



**Enabling geography:** Iceland's geography has the optimal environment for seaweed growth. With its cold, nutrient-rich waters from the Atlantic Ocean and the North Sea, fjords well suited for aquaculture, and existing kelp biomass availability for wild harvest, Iceland is a prime location for seaweed industry. Iceland is also home to nutrient dense species of kelp such as *Laminaria* and *Saccharina latissimi*, and paired with Iceland's pristine oceans, its product is ideal for high-value and premium processing.<sup>xiii</sup> Also, given Iceland's lower water temperatures, it is less likely to be affected by climate-driven kelp deforestation due to increased thermal stress, intensified grazing pressure, and decreased habitat availability.<sup>xliii</sup>



**Plentiful green energy:** Seaweed processing is highly energy intensive, especially drying and refining biomass into high-value components.<sup>xliii</sup> Iceland's abundant geothermal energy – providing half of all the primary energy used in Iceland – offers a low-carbon and cost-effective option to seaweed processing.<sup>xliii</sup> Geothermal seaweed processing for export has been in operation in Reykhólar for about 50 years and recent investments have been made in a geothermal processing a drying facility near Breiðafjörður, showing a growing interest in green energy seaweed processing in the region.<sup>xliii</sup>

<sup>1</sup> *Fucus serratus* is considered invasive in Iceland <https://www.ices.dk/advice/ESD/Pages/Icelandic-Waters-Invasive-Species.aspx>



**Synergies with maritime infrastructure and workforce:** Fishing is one of Iceland's top 3 sectors and it is the 12<sup>th</sup> largest fishing nation in the world with marine products comprising 26% of all exports in 2024 (and 35% in 2019 pre COVID).<sup>xlvii xlviii</sup> Leveraging this extensive maritime workforce and infrastructure would provide a lower-cost and faster launch into the kelp wild harvest or aquaculture industries. Additionally, co-benefits exist with combining Iceland's fisheries with kelp farming, including combined fuel use for transportation and nutrient uptake from fish waste pollution.<sup>xlix</sup>



**Decentralized seaweed market:** Iceland's kelp market is small scale and largely focused on value over volume. There is a long history of wild seaweed harvest with top producing company Þörungaverksmiðjan (Thorverk) harvesting and exporting their raw kelp (ascophyllum and laminaria) products as flakes and ground meal, as well as a number of other companies such as Tamar, Marinox, and Una harvesting fucus and *S. Latissima* species for cosmetics (See Figure in Appendix on Icelandic kelp companies). These companies, however, operate on a small scale. There is limited exploration into kelp aquaculture despite a lack of specific legislation from the government, including a € 13.5M investment in a processing plant by Icelandic Kelp (Íslandspari), but permitting remains sparse.<sup>l</sup> There is an opportunity for companies to enter the market as early adopters in aquaculture assuming the regulatory environment allows for seaweed cultivation in the future – see Recommendations section for further details.



**Climate-progressive enabling government:** Iceland has had a consistent policy landscape in climate action between administrations, publishing several national climate policies over the last few decades.<sup>li</sup> Prime Minister Katrín Jakobsdóttir has made climate a key issue for her administration, and climate change is high among national concerns.<sup>lii, liii</sup> The private sector has also taken an active role in advancing climate goals and pushing Iceland forward in the carbon sequestration and energy transition. And as seaweed grows into a viable climate mitigation strategy, Iceland is well positioned to access EU funding for climate initiatives such as the Innovation Fund, the Modernisation Fund, and the NER 300 Programme.<sup>liv</sup>



**Abundant land for facility development:** With Iceland boasting ample available land for development, the country presents an ideal environment for the establishment of facilities dedicated to seaweed cultivation and processing, further enhancing the potential for sustainable farming practices and facilitating the growth of the global seaweed industry..

### Iceland Barriers

Despite Iceland's abundant land and favorable conditions for seaweed cultivation, the nascent seaweed industry in the country faces several barriers that hinder its growth and development.



**Lack of seaweed cultivation regulatory framework:** Iceland's government has established laws and legislation regulating wild seaweed harvest but does not currently allow for ocean-based seaweed cultivation.<sup>lv</sup> Currently, seaweed cultivation is loosely regulated through the Management of Marine Resources Act and the Fisheries Management Act but lacks the clarity and permitting needed to develop projects and advance the industry. However, despite the lack of legal framework, the private sector is pushing forward and several companies have invested in trial farms throughout Westfjords limited to land-based seaweed farming.



**Wild harvest and cultivation risk at scale:** Risks for increasing industry based on wild harvest could potentially have harmful effects on natural stocks and resulting local biodiversity. The scaling required for developing an industry would be ecologically disastrous without

investments in aquaculture, and so legislation allowing and defining aquaculture development and use in Iceland would be required. Additionally, the use of non-endemic species of seaweed in aquaculture could further affect local biodiversity. Strict regulations on wild harvest and controls on species cultivation would need to be established by the Icelandic government.



**Access to financing and capital:** Seaweed harvest, cultivation, and processing are highly capital-intensive ventures that require large upfront capital expenditures for boats, machinery, and labor costs. Financing incentives will be needed to kickstart Iceland's seaweed economy. Government subsidies, tax incentives, and investment grants could encourage private investors to commit funds to the development of seaweed farming infrastructure and processing facilities. Additionally, establishing public-private partnerships and offering low-interest loans or venture capital funding could provide further financial support to entrepreneurs and businesses looking to enter the Icelandic seaweed market. By incentivizing investment in this burgeoning industry, Iceland can unlock its vast potential as a key player in the global seaweed economy while fostering economic growth and sustainable development.



**Localized processing requirements:** Seaweed needs to be dried within 72 hours after harvest, requiring a quick turnaround time from harvest to processing.<sup>lvi</sup> This requires localized processing, which brings cost and logistics challenges to the nascent Icelandic market. Establishing processing facilities closer to the cultivation sites is essential for maintaining product quality and freshness, but it also increases operational expenses due to higher land and labor costs in Iceland. Overcoming these challenges requires innovative solutions such as strategic partnerships, efficient supply chain management, and leveraging emerging technologies to optimize processing operations and mitigate associated costs.

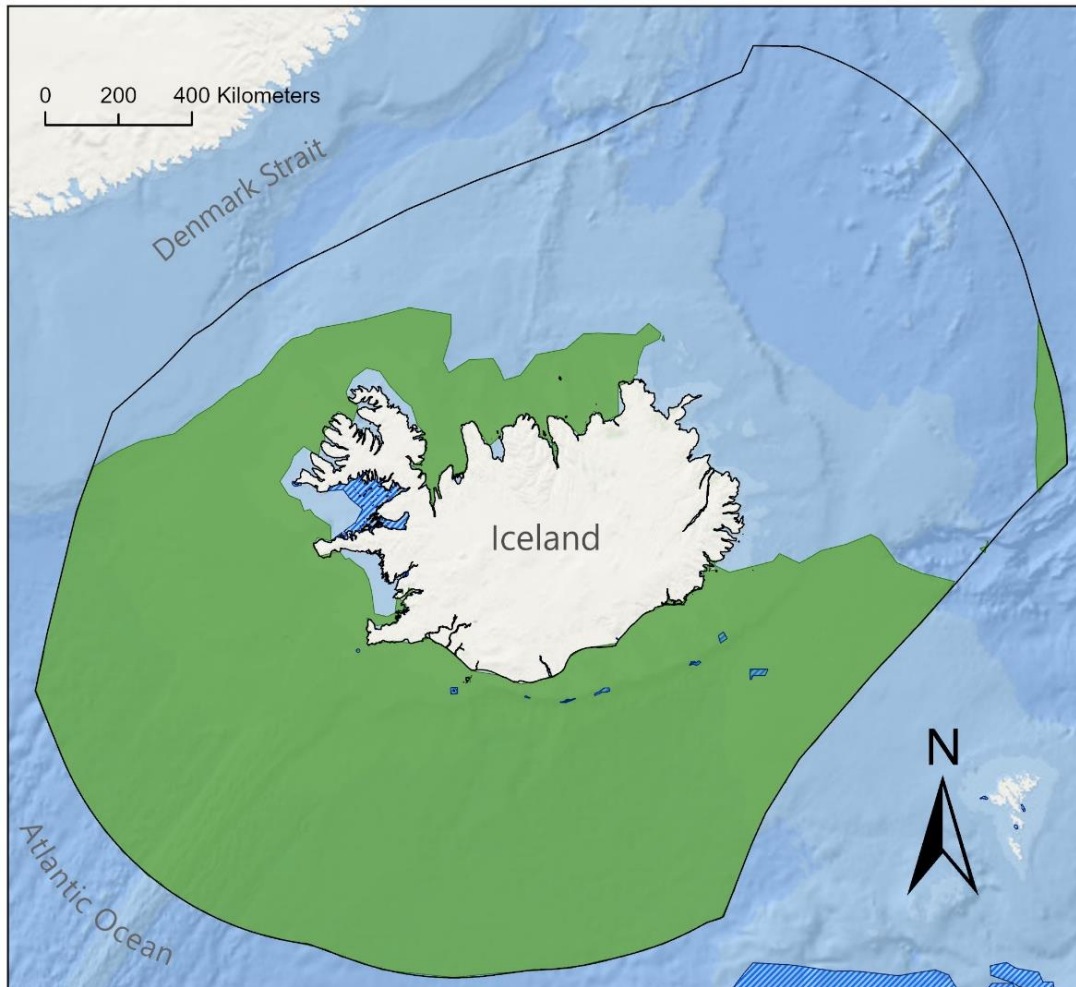


**Specialized skills and labor constraints:** Developing a seaweed industry in Iceland would require acquiring and retaining specialized expertise, processing, and related technologies that do not currently exist at scale. This is particularly true for developing an aquaculture industry given Iceland's historical investment and experience in wild harvest techniques. Addressing this challenge requires concerted efforts to invest in education, training programs, and knowledge exchange initiatives to nurture a skilled workforce capable of driving the growth and innovation of the Icelandic seaweed industry.

Despite barriers, interest in commercial seaweed farming is growing and national entities such as the Technology Development Fund in Iceland and Running Tide are supporting R&D activities for advancing Iceland's seaweed industry. Our full recommendations for developing the Iceland seaweed industry are detailed in a later section of this paper.

## Potential Kelp Aquaculture Sites in Iceland

Based on our analysis of the key characteristics of kelp aquaculture habitat parameters, Figure 9 is a map of potential kelp aquaculture sites within Iceland's Exclusive Economic Zone (EEZ) which reaches 200 nautical miles off of the country's coast. These sites meet ocean temperature, pH, and key nutrient availability requirements for growth.



### Legend

-  Iceland Exclusive Economic Zone (EEZ)
-  Iceland Marine Protected Areas (MPAs)
-  Potential Kelp Aquaculture Sites

#### Data Source Credits:

v.3.0 Assis, J., Fernández Bejarano, S.J., Salazar, V.W., Schepers, L., Gouvêa, L., Fragkopoulou, E., Leclercq, F., Vanhoorne, B., Tyberghein, L., Serrão, E.A., Verbruggen, H., De Clerck, O. (2024) Bio-ORACLE v3.0. Pushing marine data layers to the CMIP6 Earth system models of climate change research. *Global Ecology and Biogeography*. DOI: 10.1111/geb.13813

v.1.0 Tyberghein L, Verbruggen H, Pauly K, Troupin C, Mineur F, De Clerck O (2012) Bio-ORACLE: A global environmental dataset for marine species distribution modelling. *Global Ecology and Biogeography*, 21, 272–281. DOI: 10.1111/j.1466-8238.2011.00656.x

Flanders Marine Institute (2023). *Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200NM)*, version 12.

UNEP-WCMC and IUCN (2024), *Protected Planet: The World Database on Protected Areas (WDPA)* [Online], April 2024, Cambridge, UK: UNEP-WCMC and IUCN.

Figure 9: Potential Kelp Aquaculture Sites in Iceland

## Defining and Quantifying Value

As detailed before, kelp provides value in many ways from the ecological services it provides to the monetizable value from sale of products. We believe it is important to measure both market and non-market costs but consider them separately as they may be relevant to different audiences.

Since our client primarily operates in the private sector, identifying the market values of different seaweed-based products will be most useful for companies or investors looking to evaluate the attractiveness of the space. We thought it would be most helpful to provide detailed financial information, including generalized production costs, purchase prices, and margins, but we were unable to find reliable data. We learned that production costs vary widely by region and scale of operations and that financial data is not publicly available.

Similarly, we learned that prices of kelp sales are highly variable and non-transparent, with major differences across regions, species, buyers, and quality of product. In our focus area of Europe and the Nordics, the industry is nascent and there is no reliable market data as you would expect to find for other agricultural commodities. We have done our best to aggregate directional quantitative data for economic uses.

## Market Value

Enterprising growers have devised many ways to valorize kelp. These range across traditional uses such as direct human consumption, industrial uses like adding alginates to food or cosmetics, and high-tech uses such as refining seaweed into next-generation biofuels. Grand View Research estimates the 2021 market size of the global seaweed industry at \$9.9 B across all end uses.<sup>lvii</sup> In addition to commercial products, innovations in carbon and nitrogen credit programs such as Running Tide’s deep ocean sequestration project and the Long Island Sound kelp remediation program can serve as models for future opportunities to convert the non-market value of ecosystem services to market value.

We analyzed 46 global algae producing companies, sourced from Arias et al., and added insights from our literature review and expert interviews to determine the market viability for each use.<sup>lviii</sup> Of the 46 companies analyzed, 23 were based out of Europe and 29 produced brown macroalgae, which is the scope for this project. Many also produced red and green algae – we were not able to disambiguate for the use cases noted, but the general trends should be directionally informative. The most common end uses among the companies studied were “Plant & Soil Nutrition” (29 companies) and “Food Sector” (27). Other common applications include “Cosmetics / Personal Care Products” (21), “Nutraceutical & Pharmaceutical” (20), and “Animal Feed” (17). The least common, and by extension least commercially viable, applications are “Biopolymers” (5) and “Bioenergy” (2).

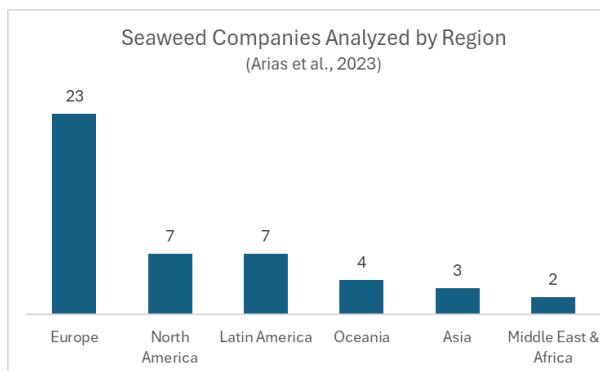


Figure 10: Seaweed Companies Analyzed by Region

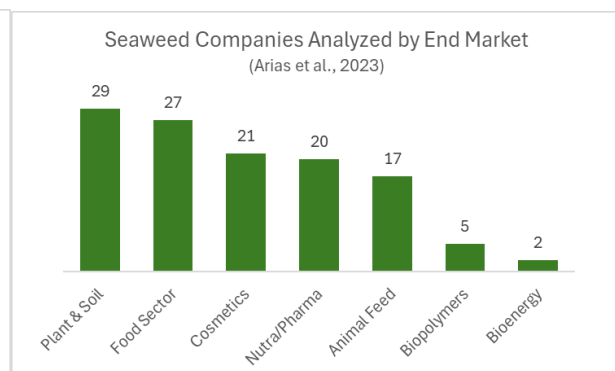


Figure 11: Seaweed Companies Analyzed by End Market

Our taxonomy differs from Arias et al., as we see the value chain differently. For example, a producer refining alginates may be creating the same raw material input that is used in food, cosmetics, and pharmaceutical uses – in this case, all three end uses may entail a similar process for the producer, who sells an intermediate product and trends in the hydrocolloid market may be more relevant than trends in the end use markets.

Figure 12, below, is a market summary informed by our literature review and expert interviews, followed by deep dive sections into each end market.

End Market	Viability for Iceland Market	Market Summary
Hydrocolloids	✓✓✓	<ul style="list-style-type: none"> <li>Alginates and fucoidans for industrial food, pharmaceutical, and cosmetics uses</li> </ul>
Biostimulants	✓✓✓	<ul style="list-style-type: none"> <li>Seaweed-based biostimulants for <b>plant growth</b> as an <b>alternative to chemical fertilizers</b></li> </ul>
Other Industries	✓✓✓	<ul style="list-style-type: none"> <li><b>Niche industries</b> from kelp-based soaps, personal care products, and ink. <b>Opportunity for entrepreneurs to create new uses for kelp</b></li> </ul>
Direct Human Consumption	✓✓	<ul style="list-style-type: none"> <li><b>Fresh seaweed</b> for restaurants/markets</li> <li><b>Packaged food products, nutrition supplements</b></li> </ul>
Animal Consumption	✓✓	<ul style="list-style-type: none"> <li><b>Livestock nutrition</b> supplements, <b>aquaculture feed</b>, <b>pet nutrition</b> supplements</li> </ul>
Blue Carbon & Environment Credits	✓	<ul style="list-style-type: none"> <li><b>Carbon market</b> is nascent and has <b>lack of scientific consensus</b> on climate benefits.</li> <li><b>Nitrogen credits</b> may be viable.</li> </ul>
Biofuels	✗	<ul style="list-style-type: none"> <li>Next-generation biodiesel and SAF, <b>not economically viable</b></li> </ul>
Biomaterials	✗	<ul style="list-style-type: none"> <li>Bioplastics and biofibers, <b>not economically viable</b></li> </ul>

Figure 12: Summary of Market Viability by End Market. Source: Researcher analysis.

## A) Hydrocolloids

**Current Economic Viability:** High



### Market Overview

The market for alginates and other algal hydrocolloids is mature, with many uses in food, cosmetics, and pharmaceuticals. The main hydrocolloids derived from brown macroalgae are alginate and fucoidan, which serve as thickening agents in foods and cosmetics, as well as active ingredients in pharmaceuticals. Agar and carrageenan from red seaweeds are not in scope for our recommendations but represent a major part of the hydrocolloid market and have a variety of uses, primarily in the food industry.

High grade hydrocolloids can be used for medical purposes. Alginates, which are considered biocompatible, can be used for wound healing, drug delivery, and tissue engineering in addition to other uses as treatment for acid reflux.<sup>lix</sup> Fucoidans, which have anti-inflammatory, antioxidant, and antiviral properties, have been used for various medical uses including being studied as a potential treatment for COVID-19.<sup>lix lxi</sup> From our interview with a researcher from KTH Institute of Technology, we learned that

the hydrocolloid industry is stable and there is widely available supply.<sup>lxii</sup> Since there are many varieties of seaweed grown around the world, biochemical properties and uses can vary across species and regions.

The market is highly commoditized, and supply is sourced mainly from Asia, although IFF (formerly DuPont Nutrition & Biosciences) has been developing supply partnerships in Norway and Iceland. Large companies dominate, including Cargill, IFF and CP Kelco. One of our interviewees managing a global pet care company’s oceans program indicated that corporate buyers may be willing to pay a price premium for higher sustainability and transparency. Seaweeds are a critical input for this growing space, supplying the base for 40% of all hydrocolloids.<sup>lxiii</sup> The estimated value of the total hydrocolloid market from seaweed is estimated at \$610 million and projected to grow to almost \$1 billion by 2023.<sup>lxiv</sup>

Opportunities in this space include developing novel uses for components from locally grown seaweed, providing sustainability-focused buyers with high-quality transparently sourced supply, and valorizing waste biomass left over from hydrocolloid processing.

**Viability for Iceland Market:** High

Many of Iceland’s existing seaweed operations are already producing hydrocolloids including Íslandsþari (based in Husavik) and Thorverk (based in Breiðafjörður), which is owned by IFFs. Through our interview with Icelandic producer Íslandsþari, we learned that Icelandic kelp produces high-quality alginate, and that ocean heating in Southern Europe may make Iceland a more attractive market to develop.

There is a need for skilled workers to process the alginate, which requires around 10 times more labor than the harvest of the kelp feedstock for a smaller operation. Our interviewee from Íslandsþari noted that the local workforce does not have the right skillset to meet their current processing needs.<sup>lxv</sup>

Icelandic producers can offer traceability, quality, and a lower GHG footprint due to emissions-free geothermal processing.

**Table 3. Active Companies in the Hydrocolloid Space Globally**

Algaia	France	Specializes in marine-based hydrocolloid solutions for various industries worldwide.
Algae	Norway	Dedicated to harnessing the power of algae for hydrocolloid production.
Cargill	USA	Multinational corporation that specializes in food, agriculture, financial, and industrial products and services, operating across the entire supply chain. Provides hydrocolloid solutions for diverse industrial applications.
CP Kelco	USA	Leading supplier of hydrocolloids for food, beverage, and other industries worldwide.
IFF	USA	Offers innovative hydrocolloid solutions for global markets, particularly in the food, beverage, and personal care sectors.
Gelymar	Chile	Prominent producer of seaweed-derived hydrocolloids for industrial applications worldwide.
SeaChange Biochemistry	Canada	Focuses on developing sustainable hydrocolloid solutions sourced from marine environments for global markets.

## B) Biostimulants

**Current Economic Viability:** High

High



### Market Overview

Raw materials biostimulants are natural substances derived from plants, seaweed, microbes, or other organic sources that enhance plant growth, nutrient uptake, and stress tolerance in crops. Extracts from seaweed account for about 40% of the biostimulant market.<sup>lxvi</sup> While seaweed has historically been used as fertilizers in localized regions, such along the west coast of Ireland, seaweed biostimulants have been gaining global attention and popularity in the agricultural industry due to their numerous benefits for plant growth, stress tolerance, and yield improvement.<sup>lxvii</sup> Seaweed biostimulants currently comprise \$1 billion of the biostimulants segment of the crop nutrition market but have yet to gain a meaningful foothold across larger-scale crops, estimated to be used on less than 0.5% of global farmland. Market analysis indicates that the global seaweed biostimulant market is expected to grow significantly with a

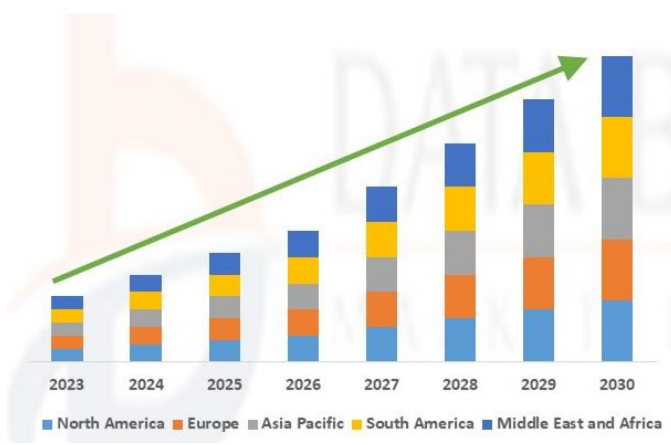


Figure 14: Global Seaweed Extracts Biostimulant Markets Expected to Reach \$2.58B by 2030. Source: Data Bridge Market Research.

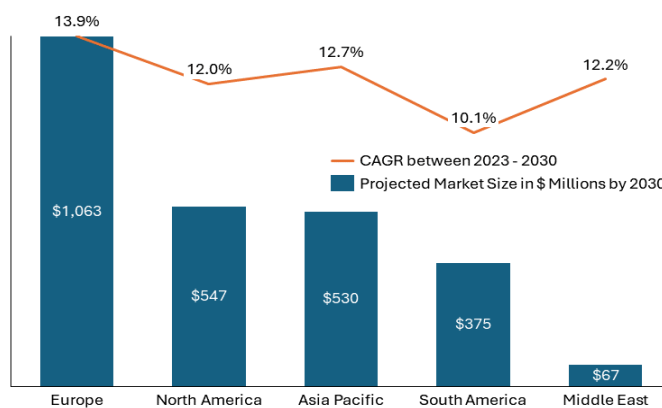


Figure 13: Seaweed Biostimulant Global Market Trends by Region. Source: Team Analysis, Data Bridge Market Research

CAGR of 12.9% and anticipated market size of \$2.5 billion by 2030, with highest growth and largest market anticipated in Europe.<sup>lxviii</sup> This high market growth is driven primarily by rising preferences for organically grown food as well as a growing awareness of sustainable agricultural practices.<sup>lxix</sup> This growth could demand up to 1 million tons of seaweed globally by 2027, a 50% increase from today's biostimulants seaweed requirements.<sup>lxx</sup>

Seaweed-based biostimulants such as giant kelp offer an organic alternative to damaging agrichemicals and are helping transform modern agriculture sustainably. Kelp-based biostimulants contain a range of beneficial compounds such as cytokinins, auxins, gibberellins, and alginates, which promote soil health and plant growth and development<sup>lxxi</sup>. Seaweed-based biostimulants also promote defense-regulating genes in crops which contribute to pest and disease resistance as well as resilience against abiotic stresses including drought, salinity, and cold.<sup>lxxii</sup> All of these benefits result in higher crop yields, which increase harvests anywhere from 50% -200%.<sup>lxxiii</sup> Seaweed biostimulants are ideally suited for organic farming and environmentally sensitive crop production, and are compatible with other crop inputs allowing for their use in sustainable integrated management approaches to reduce the use of synthetic chemical fertilizers.<sup>lxxiv</sup> Seaweed biostimulants have also been found to cut carbon dioxide emissions in half per application as compared to chemical fertilizers, making them an attractive solution to decarbonization and a reduction in other environmental impacts.<sup>lxxv</sup>

**Case Study 2. Giant Kelp at the Forefront of Transition to Sustainable Agriculture in New Zealand**

In studies run by NZ Kelp, a giant kelp harvesting company in New Zealand, barley plants that were applied with Giant Kelp biostimulants showed an average increase of 7.16% in key plant nutrients. The biostimulants also supported healthy plant-microbe soil relationships as evidenced in higher plant secretions of sugars, enzymes, and carbon. When applied to carrots, giant kelp stimulant application increased the yield by 27% resulting in a 16x return on investment (\$7,897 more revenue per hectare). When contrasted with applications of industrial chemical fertilizer, which have a negative effect on beneficial bacteria and fungi in the soil, kelp is a promising option for farmers to improve yield and endurance of their crops in the long term.

The global legislative environment for seaweed-based biostimulants is evolving rapidly as countries recognize the potential of these products in agriculture and environmental sustainability. Many nations are working to establish clear regulations and standards to ensure the efficacy and safety of these biostimulants. The European Union, for instance, has been at the forefront with legislation like the EU Fertilizing Products Regulation (EU 2019/1009) which includes seaweed-based biostimulants within its scope, and the communication from the European Commission on algae-based biostimulants.<sup>lxxvi lxxvii</sup> In the United States, the USDA has been exploring ways to include biostimulants under its National Organic Program and a recently introduced Plant Biostimulant Act of 2023 to clarify the use of plant biostimulants.<sup>lxxviii</sup> Australia has also developed guidelines for biostimulant registration and India recently issued an amendment to the national Fertilizer Control Order (FCO) acknowledging seaweed's role in enhancing crop productivity.<sup>lxxix lxxx</sup> As the benefits of seaweed-based biostimulants become more evident, global legislative bodies are expected to take steps to foster their responsible use and commercialization.

Seaweed-based biostimulants face several potential barriers in the global market. One significant challenge is the lack of awareness and understanding among farmers regarding the benefits of these products. Many farmers are accustomed to traditional fertilizers and may be hesitant to adopt new biostimulants without clear evidence of their effectiveness. Another barrier is due to the fact that the majority of seaweed used in biostimulant production is wild harvested (including *Ascophyllum nodosum*, *Ecklonia maxima*, and *Laminaria digitata*), which poses potential problems with ecosystem integrity as demand grows.<sup>lxxxi</sup> There is also a conflict between the price that biostimulant producers are willing to pay for seaweed feedstock that's price is driven by the availability of wild harvested biomass. There is also a challenge associated with normalizing across the bioactive components found in seaweed, such as peptides, proteins, and amino acids, that are affected by seasonal fluctuations and habitat. Overcoming these barriers will require concerted efforts from industry stakeholders to educate farmers, develop consistent quality standards, improve affordability, and shift the market towards farmed seaweed to increase the acceptance and use of seaweed-based biostimulants globally.

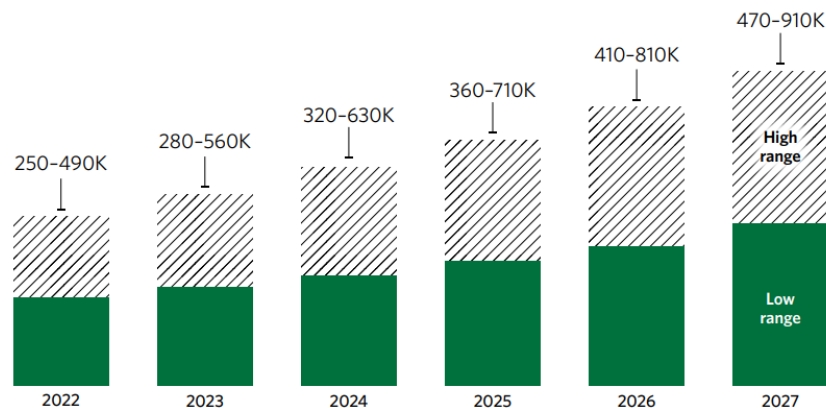


Figure 15: Estimated range of seaweed used in seaweed biostimulant production. Source: The Nature Conservancy <sup>lxxxii</sup>

### Viability for Iceland Market: High

The country's focus on sustainable agriculture and decarbonization aligns well with the environmentally friendly nature of seaweed-based biostimulants, making them an attractive option for farmers looking to enhance crop productivity while minimizing environmental impact.<sup>lxxxiii</sup> Additionally, Iceland's nutrient-rich and unpolluted waters will produce a high quality product that can be sold at a premium.

Unlike human consumption, the seaweed biostimulant market is not yet oversaturated, and fast demand growth in Europe creates opportunity for Icelandic producers. If the industry can scale production, then Iceland could be an ideal market for seaweed biostimulants.

**Table 5. Active Companies in the Seaweed Biostimulant Space Globally**

BioAtlantis	Ireland	Leading biotechnology company that focuses on the research and development of biostimulants derived from seaweed. Their products are designed to enhance crop growth, improve stress tolerance, and increase yields while promoting sustainable agriculture practices.
Algae	Norway	Specializing in the production of seaweed-based products for agriculture, horticulture, and aquaculture. Their biostimulants are derived from sustainably harvested seaweed and are designed to enhance plant growth, stress tolerance, and nutrient uptake.
NZ Kelp	New Zealand	Focused on producing high-quality seaweed-based products for agriculture, horticulture, and animal health.
Olmix	France	Dedicated to developing natural solutions derived from algae and other natural ingredients for agriculture, animal nutrition, and environmental health.
Leili Group	China	Specializes in the research, development, and production of fertilizers, agricultural chemicals, and seaweed-based biostimulants.
Acadian Seaplants	Canada	One of the largest producers of seaweed-based products for agriculture, including biostimulants. Offer a range of products derived from various seaweed species, aiming to improve plant health, nutrient uptake, and overall crop performance.
Koppert Biological Systems	Netherlands	While not exclusively focused on seaweed-based products, Koppert Biological Systems offers a range of biostimulants, including those derived from seaweed extracts. Their products are designed to improve plant resilience, root development, and nutrient efficiency.
Tradecorp	Spain	Offers a variety of biostimulants for agriculture, including some derived from seaweed extracts. Their products aim to improve plant growth, yield, and quality by enhancing nutrient uptake and stress tolerance.

### C) Other Industries

High

Current Economic Viability: Low



#### Market Overview

In our research we have come across other niche industries looking to use kelp for consumer and industrial uses, as well as kelp-adjacent industries we wanted to acknowledge.

One of the companies we interviewed is Urchinomics, who removes sea urchins that graze on kelp forests and sells their roe (known as uni) to restaurants.<sup>lxxxiv</sup> By removing the urchins, they are collecting valuable resources and helping restore degraded ecosystems.

Another company we came across is Oceanium, who uses kelp to make ink, one of the most expensive liquids in the world by gallon.<sup>lxxxv lxxxvi</sup>

Other companies are creating high-end personal care products like soaps and creams from kelp extracts.

As Western interest in kelp rises, we expect entrepreneurs to continue inventing new ways to valorize seaweed and demand for seaweed products to pick up.

#### Viability for Iceland Market: High

While it is unclear how scalable these solutions, and other novel solutions like them are, we have faith in Icelandic entrepreneurs to come up with new uses for kelp that the world hasn't seen before!

**Table 9. Active Companies in the Other Seaweed Industries Space Globally**

Algae Náttúra	Iceland	Focuses on utilizing natural resources like algae for various applications, including food, pharmaceuticals, or environmental solutions.
Marinox	Iceland	Specializes in marine-related products or services, focusing on aquaculture, marine biotechnology, or seafood processing.
Oceanium	UK	Operates within the marine biotechnology sector, specializing in seaweed cultivation, sustainable ocean resource management, or bioremediation solutions.
Taramar	Iceland	Involved in seafood processing, aquaculture, or marine biotechnology, utilizing the rich marine resources of Iceland.
Urchinomics	Norway	Focuses on marine conservation, aquaculture, or research related to sea urchins and their ecological impact and commercial potential.
Zeto	Iceland	Specializes in utilizing local resources for food, energy, or environmental solutions, potentially including seafood processing or renewable energy.

### D) Direct Human Consumption

Medium

Current Economic Viability: High



#### Market Overview

Kelp for human consumption is the most mature seaweed market, centered largely in Asia (over 97% of production) where most historic and present-day supply and demand is concentrated.<sup>lxxxvii</sup> China, Korea, and Japan have fully developed industrial-scale aquaculture operations, and strong cultural adoption of

seaweed as a culinary ingredient creates a stable commodity market. The estimated market size for seaweed for direct human consumption is \$5 billion. <sup>lxxxviii</sup>

Outside of Asia, European and American companies are using kelp for ready-made foods such as pre-packaged salads, kelp flake/powder, veggie burgers, or even infusing sugar kelp in artisanal gin. There is also a significant market for dietary supplements and nutraceuticals, such as iodine supplements made from giant kelp.

Limiting factors for kelp food products include spoilage, price, and cultural norms. From our interview with Alaska-based producer Pacific Kelp, we learned that fresh seaweed must be consumed or processed within 72 hours (about 3 days) of harvesting, or it spoils. <sup>lxxxix</sup> Seaweed growers close to major markets may be able to provide fresh product to restaurants or high-end markets, such as Maine-based companies delivering to New York and Boston, but many growers will find the potential of this market is limited due to operational constraints.

Selling processed kelp food products has its own challenges – packaged products compete against traditional proteins and vegetables in saturated grocery and specialty channels and must invest substantially in commercial capabilities to succeed. Different geographies may have more stringent standards that food products must meet, even across categories (e.g., diet supplements, nutraceuticals). Companies looking to enter the European and American markets also have to build demand for kelp-based foods because there is not an existing culture of culinary use for seaweed like there is in Asia. Prices in Western markets will likely be higher than comparable non-kelp products, due to lack of economies of scale, which may put off some consumers from purchasing expensive kelp-based products.

**Viability for Iceland Market:** Medium

Iceland benefits from high-quality kelp resources, a positive brand association, and expertise in commercializing similar ocean-based consumer products (e.g., fish skin chips, dried fish heads for soup, canned goods).

Since Iceland is currently only harvesting wild kelp, it will be difficult to reach the scale of production needed to penetrate a mass food market where it may compete with larger producers. Iceland can compete by marketing higher-value food products, pursuing certifications such as USDA Organic or MSC/ASC certifications, and advertising their “Made in Iceland” origin. An alternative is developing nutraceuticals and nutrition supplements – once the necessary regulatory approvals are secured, the same algae input can fetch a significantly higher market price.

Targeting affluent, health-conscious consumers that value sustainability and are open to trying new foods may be a successful strategy to mitigate higher production costs, marketing costs, and low general adoption. Industry-wide collaboration to grow the market may benefit all players across geographies.

Another area of focus could be on developing a robust internal market for seaweed foods. Iceland has a storied tradition of kelp consumption, and reintroducing this ingredient to the country’s food mix could address food security and increase resilience by providing ready access to a locally grown crop instead of imported foods.

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**Table 2. Active Companies in the Seaweed Consumption Space Globally**

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12Tides	USA	Crafts delicious and nutritious snacks made from sustainably farmed kelp, offering a taste of the ocean with every bite.
AKUA	USA	Pioneering food company producing tasty and sustainable kelp-based foods, championing regenerative ocean farming practices for a healthier planet.

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Atlantic Sea Farms	USA	Dedicated to sustainable seaweed aquaculture, offering a range of delicious and nutritious seaweed products sourced from the North Atlantic.
Barnacle Foods	USA	Specializes in creating innovative and sustainable food products using locally harvested kelp, bringing the flavors of the sea to the table.
Isle of Harris Distillery	Scotland	Incorporates locally sourced, hand-harvested sugar kelp into its gin production, infusing their spirits with the distinctive flavors of the surrounding Hebridean waters.
NAAS Foods	Canada	Focused on sustainable and nutritious plant-based products, their innovative approach incorporates seaweed into a variety of food products, ranging from snacks to meal solutions.
The Dutch Weed Burger	Netherlands	Mission centered around creating sustainable and delicious alternatives to traditional meat-based products, with a focus on seaweed as a key ingredient. The company's flagship product, "The Dutch Weed Burger," is a plant-based burger made from a blend of nutritious ingredients, including seaweed, soy, and various herbs and spices.
Seamore	Norway	Focused on creating innovative seaweed-based products as alternatives to traditional foods. Their flagship product, "I Sea Pasta," is made from the seaweed species <i>Himanthalia elongata</i> and offers a healthy and sustainable alternative to pasta.
Nordic Seaweed	Norway	Specializes in the cultivation and processing of seaweed for food and feed applications. They cultivate various species of seaweed, including <i>Saccharina latissima</i> , and produce a range of products such as seaweed salads and snacks.
Tang	Sweden	Tang is a Swedish company dedicated to promoting seaweed as a nutritious and sustainable food source. They offer a range of seaweed-based products, including seaweed snacks, seasonings, and spreads, all made from sustainably harvested seaweed.

## E) Animal Consumption

**Current Economic Viability:** Medium

Medium



### Market Overview:

Compounds in seaweed have been proven to be beneficial for digestion and general wellbeing for animals. Kelp is full of nutrients, and seaweed entrepreneurs have developed nutritional supplements formulated for domestic and livestock animals with promising results. Kelp is also used as an ingredient for aquaculture feed.

*Asparagopsis taxiformis*, a type of red alga, seems especially promising as a supplement to cattle feed. In a study, cattle fed a diet containing *asparagopsis* displayed significant reductions in methane, a powerful greenhouse gas many times more potent than CO<sub>2</sub> (Kinley et al. 2020, Roque et al. 2021). While the market viability of this use case has not been tested, initial results send a positive signal for the potential role of seaweed in animal diets. Across the market, our expert interviews indicate that animal feed will be one of the fastest growing segments in the next few years, and that many producers will try to enter the space.<sup>xc xci</sup>

Barriers include adoption and quantification of benefits and adverse effects. Farmers are reluctant to try untested products and want to see clear benefits before investing. One of our industry experts encourages seaweed producers to communicate the value proposition to farmers in the context of their business – using seaweed inputs to increase feed conversion ratios (food in, biomass out), reduce antibiotic use (and associated costs), or to have more productive animals.

One study concluded that when adding red algae *asparagopsis* to feed, a producer finishing 1000 head of beef cattle might save \$40,320 to \$87,320 on feed expenses.<sup>xcii</sup> Collaborating with farmers and scientists to test new feeds and generate reliable data will help spur adoption. Having more data will also help understand any side effects and ensure that adding kelp supplements to feed does not adversely affect the animal's health.

Our pet food expert indicated that their company had evaluated kelp as a primary ingredient for pet food but decided not to pursue product development.<sup>xciii</sup> We learned that pet foods are precisely formulated to provide a complete nutritional profile while still being palatable to animals, and that many pets did not like to eat seaweed. Smaller companies in this space focus on producing nutrition supplements for pets, although we have found one company offering kelp-enhanced vegan dry food. The industry experts we interviewed at Pacific Kelp mentioned that one of their most attractive customer segments is small pet food companies who produce higher-markup products and have a higher willingness to pay than more commoditized buyers.<sup>xciv</sup>

#### Case Study 3. Reaping Seaweed's Animal Nutrition Benefits

Algea, a producer based out of Norway, markets its Algeafeed line for cattle, pet, fish, pig, horse, and poultry nutrition uses. Advertised benefits range from improved digestion, increased milk yield for cows, shinier coats for pets, stronger immune systems, and eggs with stronger shells and bigger yolks. Other producers make similar claims, with varying levels of research backing them.

"Algea Is Worldwide Leader in Manufacturing Algae like *Ascophyllum Nodosum*." n.d. Algea. <https://www.algea.com/>.

#### Viability for Iceland Market: Medium

Fresh seaweed has been used as feed for animals in Iceland for centuries including sheep, cattle, and horses.<sup>xcv</sup> Ongoing research funded by the Icelandic government is studying how adding seaweed to cattle feed can increase productivity and quality of milk from dairy cows.<sup>xcvi</sup>

Similarly to the direct human consumption segment, Icelandic companies can succeed by creating high-value pet nutrition supplements and investing in branding, touting the product's high quality, sustainability, and premium Icelandic origin.

Targeting livestock feed buyers in Europe will open a larger market, but Icelandic producers will face the barriers detailed above. An option would be to partner with local livestock farmers to test and develop products, then expand to outside markets once a viable product exists. There is also an opportunity to explore production of kelp-based aquaculture feed, especially as an input for the growing Icelandic salmon aquaculture industry.

Developing the internal Icelandic market for animal nutrition from kelp, also similarly to the direct human consumption segment, could boost resilience by increasing the availability of locally grown feed while improving livestock productivity.

**Table 4. Active Companies in the Seaweed Animal Consumption Space Globally**

Algae	Norway	Produces animal consumption products, utilizing their sustainably cultivated seaweed as nutritious supplements for livestock, promoting health and sustainability in animal agriculture.
BioAtlantis	Ireland	Biotechnology company that develops and produces sustainable seaweed-based products for animal consumption, enhancing animal health and performance through natural solutions.
Acadian Seaplants	Canada	Company offering a wide range of seaweed-based products for animal consumption. Their portfolio includes feed additives, supplements, and natural fertilizers derived from sustainably harvested seaweed, promoting animal health and sustainable agriculture practices.
Halo Pets	USA	Pet food company that incorporates sustainably sourced kelp into their recipes, providing nutrient-rich and eco-friendly options for pet owners seeking wholesome nutrition for their furry companions.
Nutramara	Ireland	Specializes in producing premium seaweed-based supplements for animal nutrition. Their products are derived from sustainably harvested seaweed and offer a natural source of vitamins, minerals, and antioxidants to support the health and performance of livestock and companion animals.
Olmix	France	Biotechnology company focused on using algae and marine materials for various applications, including animal nutrition. They produce a range of seaweed-based feed additives and health products, leveraging the natural benefits of algae to improve animal growth, immunity, and digestion.
Volta Greentech	Sweden	While primarily focused on sustainable agriculture, Volta Greentech also offers environmentally friendly products for animal consumption. Leveraging their expertise in natural solutions for crops, they provide innovative seaweed-based additives for livestock feed, promoting healthier animals and reducing environmental impact.

**F) Blue Carbon and Other Environmental Credits**

**Current Economic Viability:** Low



**Market Overview:**

Out of the four main types of blue carbon, the framework for measuring carbon sequestration of kelp forests is the least developed.<sup>xcvii xcviii</sup> Our literature review suggests that research has been inconclusive on whether the carbon sequestered in biomass or deposited in deep-sea sediments is a reliable climate solution. Carbon sequestered in biomass is often released during use phase (unless used to make durable materials or biochar) which must be accounted for in the lifecycle analysis.<sup>xcix</sup> While sinking kelp into deep-sea sediments shows promise, measuring permanence and additionality is complicated due to complex interactions between oceanic and atmospheric cycles. Additionally, sinking kelp may have unintended ecological consequences and presents the ethical dilemma of sinking a valuable food source that is costly to produce.<sup>c</sup>

Our interviewee at an international NGO confirmed that the nonprofit is still researching the scientific validity of seaweed-based carbon removal claims and said that a wider market for seaweed-backed blue carbon credits is unlikely to emerge soon. He added that nitrogen credits (payments for excess nitrogen removed from waters) for kelp would be easier to validate and that a group in the Long Island Sound was piloting a project with local seaweed farmers. <sup>ci cii</sup>

Markets for similar nitrogen credits are scarce. In a pilot project in the Chesapeake Bay, where oyster farmers could sell “nutrient credits” to polluters, the market quickly declined when water treatment plants upgraded their operations and started generating and selling credits in much higher quantities than the oyster farmers. The influx of new credits, and loss of a major potential buyer, flooded the market and the price of credits decreased. Additionally, the market for these credits was voluntary, which also resulted in a low price. <sup>ciii</sup>

Running Tide is the most notable player in this space and has seen success having recently delivered over 21,000 tons of CO2 storage through their Iceland-based operation to corporate buyers such as Microsoft, Stripe, and Shopify, all of which have announced pioneering carbon removal funds. <sup>civ</sup> Note that Running Tide uses many pathways to deliver these credits – including ocean alkalinity enhancement and terrestrial biomass sinking, which are not in the scope of this analysis. Although they partner with academic institutions and governments, and conduct ongoing testing, their solution remains controversial with the broader scientific community. <sup>cv</sup>

To our team’s knowledge, the Running Tide’s model has not been replicated at scale elsewhere, and there are not many companies attempting to. From our literature review, we were only able to find Southern Ocean Carbon, a company looking to produce biochar from seaweed for carbon credits and create a biodiversity credit market, and Pull to Refresh, another company looking to sink seaweed into deep-sea sediments. <sup>cvi cvii</sup>

**Viability for Iceland Market: Low**

Although Running Tide is an Icelandic success story in this space and has already sold their seaweed-based credits on the voluntary carbon market, the lack of scientific consensus of the viability of seaweed sinking as a climate solution coupled with concerns of sinking valuable biomass leads our team to recommend further research before new ventures enter this space. <sup>cviii</sup>

Researchers at Running Tide, partnering closely with public and academic institutions in Iceland, are actively working to collect field data and study the ecological and climate-related dynamics of seaweed sinking at scale to reduce risk and uncertainty in the model. They are also sharing data with the broader ocean community including regulators, relevant government agencies, and municipalities. If future research yields positive results, Iceland will be poised to be a global leader in seaweed-based blue carbon solutions as a pioneer in this market.

Current viability for other types of environmental credit markets is also low. Nitrogen and biodiversity credit markets for seaweed are not mature anywhere else in the world, and we have not seen any indication that the Icelandic government is interested in pursuing these solutions.

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**Table 8. Active Companies in the Blue Carbon & Environmental Credits Space Globally**

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Running Tide	USA	Dedicated to mitigating climate change by sinking seaweed to sequester carbon dioxide from the atmosphere. They harness the natural carbon-capturing capabilities of seaweed to help combat global warming while supporting marine ecosystems.
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Southern Ocean Carbon Company	Australia	Focuses on carbon capture and storage solutions, particularly in the Southern Ocean region. They employ various techniques to sequester carbon dioxide from the atmosphere, contributing to climate change mitigation efforts.
Pull to Refresh	USA	Another company exploring seaweed biomass sinking technology to lower CO2 emissions in the atmosphere.

## G) Biofuels

**Current Economic Viability:** Very Low



### Market Overview:

The biofuels market is estimated to be \$117 billion globally and growing fast as the hard-to-abate transportation sector looks at developing lower-impact feedstocks for their operations.<sup>cxix</sup> While most biofuels today are refined from corn and soy, the industry is looking at waste products, seaweed, and genetically engineered crops as alternatives for the future.

On paper, seaweed has many advantages as a feedstock due to its fast growth and lack of competition for

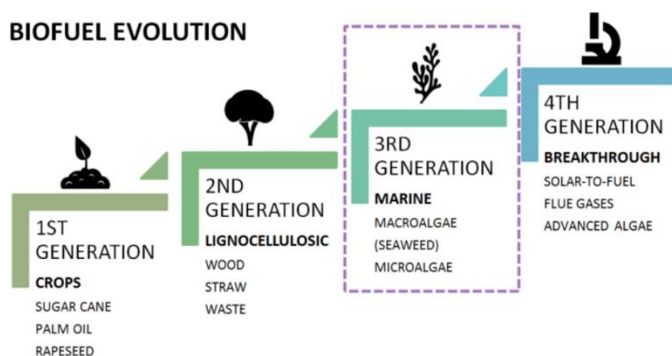


Figure 16: Generations of biofuel feedstocks. Source: Bellona.org

arable land and fresh water. Species like sugar kelp and sargassum are promising feedstocks due to the high carbohydrate content that can be fermented into bioethanol or sustainable aviation fuel (SAF).<sup>cx, cxix</sup> Biofuel production can also happen alongside other methods of kelp valorization. Current processes use approximately 30% of algal biomass, and the leftover 70% can be kept for alternate uses.<sup>cxii</sup>

The main limitation to scale seaweed-based biofuels is cost, which can be many times higher than comparable corn ethanol.<sup>cxiii</sup> As a comparison, around 40% of US corn is used for biofuel – kelp is not grown anywhere near the same scale.<sup>cxiv</sup> Of the companies we reviewed, only 2 are producing seaweed-based biofuels, partially funded by the US advanced energy technology agency ARPA-E.<sup>cxv</sup> Kelp cultivation and biofuels research would need to scale massively to reach cost competitiveness with current feedstocks.

Additionally, there are concerns that biofuels may end up having higher net environmental impacts when the full lifecycle of production, processing, and biorefining is considered. Although seaweed can be a lower-impact source of biomass, there is still a high loss of energy when it is converted to fuel. The refining process is energy intensive and often uses strong chemicals which also contribute to the impact of biofuels.<sup>cxvi</sup> Iceland may be a good application for local processing and specialized use cases given the abundant geothermal energy needed for the liquefaction process.

**Case Study 4: Biofuel from Kelp and Fish Waste Products**

In search of a cheaper, sustainable fuel, researchers at Pacific Northwest National Laboratory (PNNL) turned to two plentiful marine resources in Alaska: kelp and fish processing waste. Researchers found that by using existing fish processing plants, Alaska’s kelp harvest and fish waste can be transformed into a diesel-like fuel that is carbon neutral after higher value products are recovered. This fuel – an expensive and seasonally scarce resource for Alaskan communities – could then be used to power generators or fishing boats. Cost can be between \$3.18–3.64 per gallon, depending startup costs, which is significantly cheaper than the roughly \$7 per gallon for fuel that must be flown in. The resulting biofuel is highly oxygenated which requires additional steps and hydrogen to convert into a higher-quality fuel for diesel trucks, driving up costs, but is great as a maritime fuel replacement or to power generators. This use case could apply to Iceland which could use the geothermal liquefaction to power the fuel processing, driving down costs and decarbonizing the maritime sector.

**Viability for Iceland Market: Low**

High processing complexity, lack of economies of scale, and low-margin outputs put Iceland at a severe disadvantage in a market where no companies have commercially viable solutions. Icelandic producers doing wild harvest would likely run through the country’s entire kelp stocks long before reaching the scale needed to compete in biofuels.

Our interview with an energy professor at the Duke Nicholas School of the Environment indicates that there may be long-term viability to use seaweed as an input for higher-value SAF if price can be lower than competitive feedstocks.<sup>cxvii</sup> Even in a future market where SAF can be economically made from algae, the industry economics would still reward mass production that will be difficult for Iceland to reach.

In the local context, however, a combined kelp and fish waste product-based fuel could replace diesel used to power maritime activities and generators much like was done in Alaska (see Case Study 4). This localized solution could augment existing infrastructure and geothermal energy to drive down costs and to help decarbonize Iceland’s fishing and maritime sector.

**Table 6. Active Companies in the Biofuels Space Globally**

Fearless Fund	USA	Develops global solutions to the challenges of marine and estuarine systems, harnessing the ocean’s potential to produce energy and sustainable products while pioneering the removal of carbon dioxide (CDR).
Marine BioEnergy	USA	Involved in the development and implementation of bioenergy solutions sourced from marine resources. Focused on harnessing the energy potential of marine biomass, such as algae or seaweed, to produce sustainable biofuels or other forms of renewable energy.
Seaweed Energy Solutions	Norway	Company specializing in seaweed cultivation for various applications, including biofuels. They focus on sustainable seaweed farming practices and research to develop seaweed-based biofuels as renewable energy sources.
Algae Biomass Organization	USA	Non-profit organization dedicated to promoting the development of algae-based technologies, including seaweed for biofuels. They work with companies and researchers to advance the use of seaweed as a renewable source of biofuels.
MarinTrust		Certification program that includes seaweed cultivation for biofuel production. They certify companies that adhere to sustainable and

		responsible practices in seaweed farming, ensuring the biofuel derived from seaweed meets strict environmental standards.
Inventwood	Sweden	Company that explores the potential of seaweed as a renewable resource. They are researching and developing technologies to convert seaweed into biofuels, contributing to the sustainable energy transition.

## H) Biomaterials

**Current Economic Viability:** Very Low



### Market Overview

The bioplastics market is similar to the biofuels in many ways – characterized by commoditized global markets, thin margins, and companies looking to replace cheap petroleum-based feedstocks with lower-impact alternatives. The bioplastics market is estimated to be \$96 billion globally and is expected to grow significantly as the packaging industry looks for alternatives to conventional plastics.<sup>cxviii</sup> Top CPGs including Nestle and Kellogg are announcing ambitious commitments and seeking partnerships to reduce their impact from packaging.<sup>cxix cxx</sup>

Like biofuels, seaweed has similar benefits and disadvantages when it comes to biomaterials. Biomass producers need to drive massive scale to go down the cost curve and offer supply at a competitive price. Kelp is competing against other feedstocks such as agricultural, industrial and forest waste, which are currently found in much larger quantities. Kelp can also be used to produce textiles but would be competing in a saturated space with cheaper alternatives such as cotton, linen, and synthetic fibers.

Long-term the biopolymers market could be a moderately attractive for seaweed, but current viability is low. Current companies in the space have not launched commercially, are offering very basic products, or in the case of seaweed-based fashion are selling to niche markets. SeaChange, based out of Canada, mentions bioplastics on their website but only markets their hydrocolloid products.<sup>cxxi</sup> Rhodomaxx, based out of Malaysia, is still seeking partners to test their early-stage products.<sup>cxvii</sup> Keel Labs, a startup based out of North Carolina, markets a fabric made from over 75% called Kelsun.<sup>cxviii</sup>

### Viability for Iceland Market: Low

Like biofuels, the economics of the biomaterials space rewards industrial-scale production that will be difficult to achieve in Iceland. The barriers of high complexity, high cost, and low margins make this an unattractive market to enter. Current methods of wild harvest are not well suited for large-scale uses, but niche market uses may be viable if Iceland develops aquaculture operations. However, our stakeholder interview with a blue economy investor at Transition Labs indicated that some Icelandic companies are conducting early-stage studies of kelp-based bioplastics.<sup>cxvii</sup> Marea, based out of Reykjavík, is developing algae-based bioplastics and won a finalist spot in the Tom Ford Plastic Innovation Prize competition.<sup>cxviii</sup> Their products are not commercially available yet.<sup>cxvii</sup>

There may be opportunity for astute entrepreneurs to market artisanal apparel made from kelp, like Icelandic company Nanna Lin selling leather derived from salmon skins.<sup>cxviii</sup> Use cases will likely remain niche.

**Table 7. Active Companies in the Biomaterials Space Globally**

Keel Labs	USA	Technology company that specializes in innovative solutions or software development, focusing on maritime or ocean-related applications.
Loliware	USA	Produces biodegradable and edible alternatives to single-use plastic products, such as straws and cups, made from seaweed-based materials.
Noptla	UK	Tech startup focused on ocean-related technologies specializing in data analytics, monitoring systems, or sustainable solutions for marine environments.
Marea	Iceland	Company that designs algae-based sustainable solutions that replace packaging to impact the present and the future.
Origin by Ocean	Finland	Focuses on sustainable solutions derived from marine resources, such as algae or seaweed, for various applications ranging from food and agriculture to pharmaceuticals and cosmetics.
Renovare	Mexico	Dedicated to environmental sustainability or renewable energy solutions with a focus on ocean conservation or marine renewable energy technologies.
Rhodomaxx	Malaysia	Company specializing in the cultivation or utilization of marine algae or seaweed for commercial purposes, such as food additives, nutritional supplements, or bioplastics.
SeaChange Biochemistry	Canada	Dedicated to developing and supplying cutting-edge hydrocolloid solutions derived from marine sources for global markets.
Sway Seaweed Packaging	USA	Produces eco-friendly packaging solutions made from seaweed-based materials, providing sustainable alternatives to traditional plastic packaging.

## Co-Benefits of Seaweed

Kelp offers a myriad of benefits beyond its traditional market value. Benefits extend to ecological, environmental, cultural, and societal advantages, making kelp a vital component of marine ecosystems, economies, and human well-being. While ecosystem services are not monetizable in most cases, they are crucial for sustaining life on Earth, supporting biodiversity, regulating our climate, and providing essential resources and services that underpin human well-being.

### Habitat and biodiversity function

Kelp forests provide a diverse habitat for a multitude of marine species and are considered biodiversity hotspots. They offer shelter, food, and breeding grounds for various fish, invertebrates, and marine mammals. Aside from the ecosystem services kelp provides, its habitat integrity has direct effects on market factors. For example, valuable fishery species such as spiny lobster, abalone, rockfish, and pollack rely heavily on kelp forests, and declines in kelp populations have been directly linked to declines in these genera.<sup>cxviii</sup> Protecting kelp forests therefore supports biodiversity and sustains healthy ocean ecosystems crucial to environmental wellbeing and coastal livelihoods. Our literature review showed an instance where researchers included the economic value of commercial fisheries dependent on kelp forests in the valuation for local seaweed stocks.<sup>cxix</sup>

## Bioremediation and nutrient cycling

Kelp helps maintain water quality by filtering out pollutants and excess nutrients and plays a critical role in deep-sea nutrient cycling. This is particularly important for areas with agricultural runoff, where kelp absorbs nitrogen and phosphorous pollution from fertilizer contamination and re-oxygenates the aquatic environment through photosynthesis.<sup>cxxx</sup> The presence of kelp can improve clarity and oxygen levels in the surrounding water, benefiting both marine life and human activities such as fishing and recreation. Kelp's particularly high uptake of nitrogen is associated with a potentially high value application for bioremediation or nutrient credit schemes.<sup>cxxxi</sup>

### Case Study 5: [NY State's Nitrogen Credit Program](#)

In 2021, New York offered its first ever nitrogen credit payments to oyster farmers cultivating kelp to reduce water pollution. This first of its kind partnership with the School of Marine and Atmospheric Sciences (SoMAS) and PeconicBay Keeper issued credit payments to Peconic Estuary Farmers for their sugar kelp cultivations across 10 different oyster farms. The farms produced 10,000 pounds of kelp that can be scaled up to remove up to 200 pounds of nitrogen and earn marine farmers hundreds of dollars in credits during their off season. These innovative credits provide an additional revenue stream to the oyster farmers and incentivizes seaweed cultivation to improve water quality and combat harmful algal blooms.

## Coastal protection and climate resilience

The dense structure of kelp forests acts as a natural buffer against coastal erosion. They reduce the impact of waves and storms, stabilizing shorelines and protecting coastal communities from damage due to erosion and storm surges.<sup>cxxxii</sup> Kelp forests also serve as a microclimate buffer to climate-driven ocean acidification by providing crucial relief to marine creatures such as crustaceans and mollusks, allowing them to gradually adapt to acidic conditions.<sup>cxxxiii</sup> As climate change threatens marine ecosystems, kelp's resilience to changing ocean conditions, such as temperature and acidity, will be crucial for coastal communities.

## Socio-economic value

While not directly marketable, kelp provides economic opportunities through ecotourism, research, local economies, and education. People visit kelp forests for diving and snorkeling, generating jobs and income for local communities, and research on kelp's properties also fuels innovation in fields such as pharmaceuticals, biofuels, and sustainable agriculture. Kelp also supports local fishery economies, supporting coastal livelihoods. Cultivating kelp through aquaculture also contributes to food security, offering a nutritious and renewable alternative to land-based agriculture.<sup>cxxxiv</sup> Kelp holds cultural significance for many coastal communities around the world and is used in traditional cuisines, crafts, and medicines.<sup>cxxxv</sup>

## Carbon sequestration

While the net contribution of macroalgae to carbon sequestration is hotly debated, these ecosystems are estimated to sequester about 634 million tons of

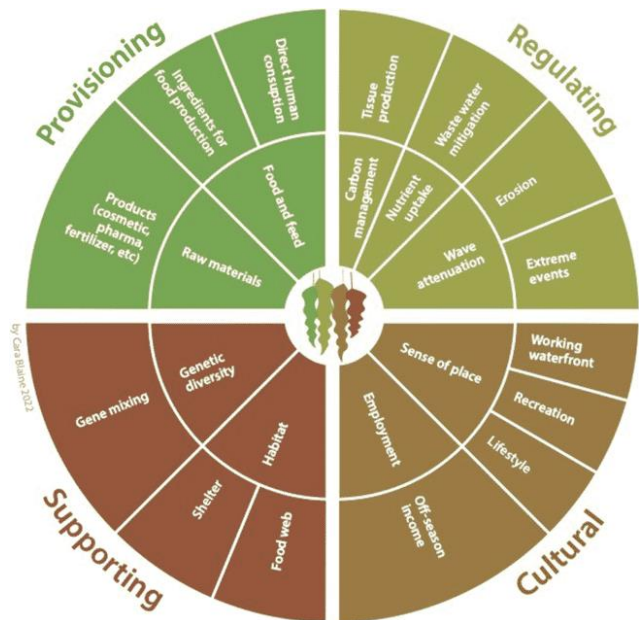


Figure 17: Visual Representation of Ecosystem Services Provided by Kelp. Source: [The Fish Site](#)

CO<sub>2</sub>e<sub>q</sub> annually (equivalent to two-thirds of total emissions from the U.S. industrials sector) in coastal sediments and the deep sea.<sup>cxxxvi cxxxvii</sup> Brown macroalgae, or kelp, in particular are dominant contributors to arctic sediment carbon stocks, highlighting their substantial role in long-term carbon sequestration.<sup>cxxxviii</sup> Nordic kelp forests store 2.7 million tons of carbon dioxide in long-term or permanent carbon storage, noting the importance of kelp for Iceland reaching 2030 Paris Agreement and 2040 carbon neutrality goals.<sup>cxxxix cxl</sup> While kelp forests have been overlooked as CO<sub>2</sub> fixing mechanism in current methodologies and standards, it has a potential as an emerging solution due to its scale, growth rate, and low energy costs compared to other direct air capture (DAC) solutions.<sup>cxli</sup> A body of peer-reviewed research exists that quantifies CO<sub>2</sub> abatement potential, but further research is required to push kelp forward as an implementable carbon capture solution.

These non-market benefits underscore the importance of preserving and restoring kelp ecosystems not only for their economic potential but also for the myriad ways they enhance our environment, mitigate climate change, and improve our quality of life.

## Recommendations for Icelandic Kelp Market

The main systemic barriers for Iceland’s kelp industry are the lack of regulatory framework (including no established licensing system for macroalgae aquaculture), access to finance, and demand uncertainty. Although we believe there is strong potential for individual enterprises to succeed in this space, resolving these systemic issues is crucial to develop a sustainable kelp industry and set all players up to succeed. Our recommendations are as follows:

### Develop a National Strategy for Seaweed

The current landscape of small-scale suppliers relying on wild harvest has limited room to grow. In a space where scale drives competitive advantage, limiting the industry to wild harvest stunts Iceland’s potential to capitalize on growth at best and threatens to degrade valuable ecosystems at worst.

Iceland can learn from governments in neighboring countries to create favorable regulatory and permitting frameworks to encourage growth and develop the country’s aquaculture potential. Policy learnings from Norway, the Faroe Islands, Denmark, and Scotland are detailed in “The State and Future of Aquaculture in Iceland” report, published by the Ministry of Food, Agriculture, and Fisheries in partnership with Boston Consulting Group.<sup>cxliii</sup> Regional governments in US states, such as Maine and Alaska, and Canadian provinces, such as British Columbia can also provide examples on successful regulatory frameworks.

We recommend the Icelandic government integrate a National Strategy for Seaweed into their National Strategy for Sustainable Development addressing these key topics.

- **Permitting:** Introduce legislation to develop a permitting system for seaweed aquaculture with appropriate resources to ensure thorough review of operations and quick application processing once all necessary conditions are met. A well-designed permitting process would allow the industry to grow and ensure long-term security for seaweed producers.
- **Regulations:** Define a science-based regulatory framework to ensure that wild harvest and seaweed aquaculture is done sustainably. Guidance on seaweed species to cultivate (e.g., preventing introduction of invasive species), harvesting methods, and inclusion of local communities will help minimize potential negative environmental impacts and ensure that industry growth benefits communities. Well-defined guidelines could also speed up the permitting application process.

- **Funding:** Increasing funding to research and development for production techniques, valorization processes, and supporting new businesses will de-risk new ventures, increase productivity, and invite private investment to grow the industry.
- **Developing the Internal Seaweed Market:** Iceland can benefit from growing internal demand for food, livestock feed, and aquaculture feed. Strong domestic demand would provide steady income for producers, while reducing dependency on imported goods and increasing Iceland’s resiliency for key inputs.
- **Workforce Development:** Create partnerships with seaweed companies and academic institutions to develop skill-building programs for seaweed aquaculture and processing. Access to a skilled workforce will help the sector grow while creating local jobs.

### Focus on Developing and Producing High-Value Products

Iceland does not have the scale required to compete with larger seaweed-producing countries on commodity products (for scale, China’s aquaculture industry produces 10x the biomass of Iceland’s entire wild seaweed stocks *annually*).<sup>cxliii cxliv</sup> Focusing on developing branded, sustainably certified, or innovative products will increase the margins producers will be able to capture from their crops.

The best species for cultivation are sugar kelp (*Saccharina latissimi*) and winged kelp (*Alaria esculenta*). Both species are highly suited for cultivation in Iceland as naturally occurring species with high yields, and rich nutritional content.<sup>cxlv cxlvi</sup>

Corporate buyers are looking for high quality inputs with a low-emissions footprint and a transparent sourcing process. Icelandic producers, with clean, productive waters, plentiful geothermal energy, and strong supply control, can provide these.

Iceland can also continue developing high-value branded consumer goods, such as the kelp-based personal care products marketed by Algae Náttúra. With Iceland’s favorable perception of “pristine” natural resources and its international tourism industry, there is high potential to grow in niche spaces. Additionally, increased research and development may create new product opportunities in the nutraceutical and pharmaceutical spaces.

### Invest in Valorization and Circularity

Innovating better processes will help create the conditions needed for high-value products development.

Producers who develop sophisticated processing and commercialization capabilities can capture multiple revenue streams from the different components of kelp. Investments in processing, biorefining, and product development can significantly increase the value extracted.

There are also opportunities to

integrate kelp aquaculture into existing value chains, particularly through Integrated Multi-Trophic Aquaculture (IMTA), where seaweed is cultivated along other species. Although IMTA is significantly more complex than traditional aquaculture, it can contribute to a circular aquaculture sector, increasing efficiency and reducing impact from waste.<sup>cxlvii</sup> In an IMTA system, seaweeds use excess nutrients from

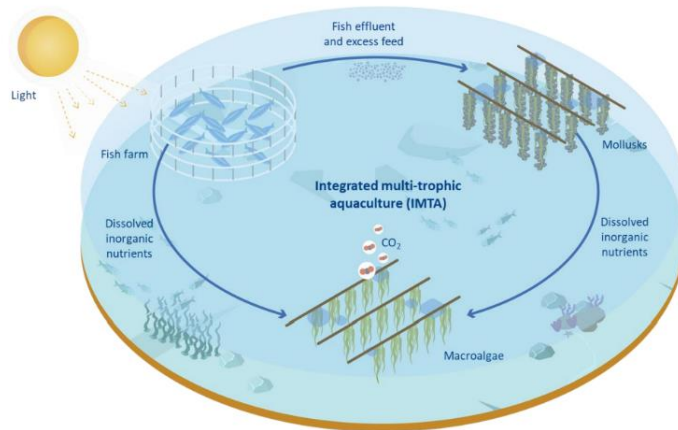


Figure 18: Integrated Multi-Trophic Aquaculture. Source: Government of Iceland

fish aquaculture to grow, and the harvested seaweed can be used as an input for aquaculture feed or sold for other commercial purposes.

## Acknowledgment of Potential Drawbacks

While seaweed markets in Iceland present promising opportunities, it is crucial to acknowledge potential drawbacks. One concern is that expanding the kelp industry can upset the delicate ecological balance of ecosystems, which could be disrupted if wild harvesting is not carefully managed. Additionally, large-scale aquaculture farms can have potentially negative impacts on benthic communities – particularly those in estuaries, lagoons, or small bays – by decreasing light and nutrient availability and slowing water motion which can impact plants and animals living on the sea floor.<sup>cxlviii</sup> Environmental impact assessments should be conducted to ensure minimal effect of wild harvest bounties and seaweed farming on ecosystem function. Also, aquaculture presents concerns with introducing non-native species for kelp farming, and so an emphasis should be placed on growing species local to Iceland waters. From a markets perspective, an emerging seaweed market may face challenges related to market demand fluctuations and competition. Balancing sustainable harvesting practices with economic viability will be essential to ensure the long-term success and environmental integrity of Iceland's kelp market.

## Areas for Further Research

### Iceland

Some potential areas of future research related to seaweed markets in Iceland could include:

- **Seaweed Species Cultivation:** Research on the cultivation of specific seaweed species that are particularly well-suited to Icelandic waters and climate and their uses across various products. This could involve optimizing environmental conditions, understanding growth rates, and identifying the most beneficial species for various applications.
- **Market Demand and Consumer Preferences:** Researching market demand for seaweed-based products both domestically and internationally. Understanding consumer preferences, such as for organic or sustainably sourced products, could guide marketing strategies and product development.
- **Aquaculture vs. Wild Harvest Environmental Impact Assessment:** Studies on the environmental sustainability of seaweed aquaculture cultivation vs. wild harvest in Icelandic waters. This could involve assessing the ecological impact, carbon sequestration potential, and potential benefits to marine ecosystems and would support aquaculture legislation.
- **Regulatory Framework Benchmark Analysis:** Research on existing regulatory frameworks and policies related to seaweed cultivation and biostimulant use in Europe to inform Icelandic policies. This could include evaluating existing regulations, proposing improvements, and assessing how Iceland's policies align with EU and global standards.
- **Value-Added Product Development:** Exploring the development of new value-added products from seaweed, such as cosmetics, pharmaceuticals, or food products. This diversification could open up new markets and revenue streams for Icelandic seaweed producers. This could also have circular economy applications if new synergies or uses are developed from existing algae waste product.
- **Geospatial Mapping of Iceland's Fish Aquaculture Sites:** Our analysis of the potential kelp aquaculture sites would be strengthened by adding a layer of fish aquaculture sites due to the potential for co-benefits. A geospatial mapping layer of currently active fish aquaculture sites

within Iceland's EEZ would narrow down potential kelp aquaculture sites even further, and is a recommended next step for determining possible locations.

These areas of research could contribute to the growth and sustainability of Iceland's seaweed markets, fostering economic development while promoting environmentally friendly practices in agriculture and beyond.

## Global

Looking at the seaweed market as a whole, there are several areas of key research needed to better understand environmental and market dynamics:

- **Stakeholder analysis for policy development:** Better understanding the strategic priorities for governments, the process of creating algae-focused policy, avenues to access government financing, and the timelines for policy implementation would help guide communication between public and private sector actors and develop a roadmap for a sustainable seaweed industry. Interviews with key experts in this space would provide a good basis of understanding for development of an enabling regulatory framework.
- **Seaweed carbon sequestration rates:** Seaweed certainly plays a role as a global carbon sink, but the amount and longevity of carbon stored in seaweed biomass, exudates, and deep ocean sediment is highly debated. Seaweed sequestration rates are also contingent on biotic interactions, prevailing winds, ocean currents, and local topographies and cause high levels of uncertainty when estimating sequestration rates.<sup>cxliix</sup> An accurate estimate of algal sequestered carbon needs further verification to improve estimates for potential blue carbon applications in the future.<sup>cl</sup>
- **Seaweed market features:** One of the earliest issues our research team ran into when trying to determine the value of seaweed was the amount of variability between products and regional markets. For example, kelp in XX cost YY while kelp in XX cost YY. Further research into standardizing the price or value of seaweed would be necessary in order to determine any kind of cost curve or market analysis. Additionally, further primary research into buyer perspectives across the various end use markets would be particularly valuable to understanding potentially attractive seaweed markets.
- **Collaborative Research Projects:** Encouraging collaborative research projects between academia, industry, and government to leverage expertise and resources. This could lead to innovations in seaweed cultivation techniques, product development, and market strategies.

Further research is essential for a comprehensive understanding of the dynamics of seaweed industry, paving the way to further decarbonize across industries globally.

## Conclusion

As a planet, we are rapidly approaching the point of no return regarding anthropogenic-driven climate change. On our current trajectory, we will reach global tipping points by mid-century.<sup>cli</sup> It is imperative for countries and companies to find both short and long-term solutions to emissions reductions in order to avoid catastrophic consequences of global warming. Seaweed – specifically brown macroalgae species like kelp – can not only provide a decarbonization solution to many high-emitting sectors, but also has a myriad of co-benefits critical to supporting functioning communities and ecosystems. Kelp is a low input high value product that should be explored by countries like Iceland who have naturally enabling geography and sociopolitical factors that would augment and bolster an emerging seaweed industry. As a leader in blue economy, green energy, and entrepreneurship, Iceland is an ideal candidate to grow the seaweed industry nationally and throughout European markets. Working with the government, industry,

and communities to sustainably grow this exciting and nascent industry would make Iceland a further leader in sustainable commerce. Investing in seaweed industry, particularly within nations like Iceland, not only offers a tangible pathway to mitigate climate change but also signifies a bold commitment towards fostering a sustainable future for generations to come. Let us seize the opportunity to harness the power of seaweed, forging a path towards a greener, more resilient future.

# Appendix

## Literature Review

### Purpose

The purpose of this research plan is to ensure that our research review is systematic, comprehensive, and replicable

### Research Question (WIP)

MP project is exploring the economic and impact potential of kelp in and around Iceland. This is in the lens of blue carbon credits, biodiversity/co-benefits, coastal resiliency, etc. while being used for economic purposes (beauty, food, health). We are working with the Iceland Ocean Cluster, which is an oceans incubator based in Reykjavik. This is through the Nicholas School but advised by a Fuqua faculty member.

### Target Databases

<b>Web of Science</b>	Interdisciplinary scholarly database with peer reviewed literature and top-tier indexed journals
<b>Environment Complete (EBSCO)</b>	Interdisciplinary scholarly database with peer reviewed literature and top-tier indexed journals
<b>Earth, Atmospheric &amp; Aquatic Science Collection (ASFA) (ProQuest)</b>	Grey literature search beyond peer reviewed journal articles – includes sports, news articles, conference proceedings, books
<b>Google Scholar</b>	Grey literature search

### Keywords

1. **Kelp terms:** kelp\* OR seaweed\* OR macroalga\* OR Phaeophyceae OR “blue forest\*” OR “marine forest\*”
2. **Carbon credit & sequestration terms:** "blue carbon" OR “carbon sequestration” OR “carbon neutral\*” OR “coastal carbon” OR (carbon AND credit\*)
3. **Economic terms:** econom\* OR “blue economy” OR (“co-benefit\*” AND (beauty OR food OR health)) OR biodivers\* OR “coastal resilien\*” OR (erosion AND coast\*) OR (coast\* AND protec\*) OR touris\* OR recreation\*

To note, we initially defined geographic keyword search terms as Iceland OR Nordic OR "Northern Europe" OR “North Atlantic” OR “Greenland Sea” OR “Iceland Sea” OR “Denmark Strait” but did not include these as they narrowed the scope too much.

**Search strategies**

Database	Search strategy	Results
1. Web of Science	<p>TS=(kelp* OR seaweed* OR macroalga* OR Phaeophyceae OR "blue forest*" OR "marine forest*") AND</p> <p>TS=("blue carbon" OR "carbon sequestration" OR "carbon neutral*" OR "coastal carbon" OR (carbon AND credit*)) AND</p> <p>TS=(econom* OR ("co-benefit*" AND (beauty OR food OR health)) OR biodivers* OR "coastal resilien*" OR (erosion AND coast*) OR (coast* AND protec*) OR touris* OR recreation*)</p> <p>TS=Topic (title, abstract, keywords)</p>	<p>11/6/2023</p> <p>109 results</p> <p>*Does not include geographic terms</p>
Environment Complete	<p>(kelp* OR seaweed* OR macroalga* OR Phaeophyceae OR "blue forest*" OR "marine forest*") AND</p> <p>("blue carbon" OR "carbon sequestration" OR "carbon neutral*" OR "coastal carbon" OR (carbon AND credit*)) AND</p> <p>(econom* OR ("co-benefit*" AND (beauty OR food OR health)) OR biodivers* OR "coastal resilien*" OR (erosion AND coast*) OR (coast* AND protec*) OR touris* OR recreation*)</p> <p>*search in Title, Abstract, or Keywords</p>	<p>11/6/2023</p> <p>29 results</p> <p>*Does not include geographic terms</p>
Earth, Atmospheric & Aquatic Science Collection	<p>(kelp* OR seaweed* OR macroalga* OR Phaeophyceae OR "blue forest*" OR "marine forest*") AND</p> <p>("blue carbon" OR "carbon sequestration" OR "carbon neutral*" OR "coastal carbon" OR (carbon AND credit*)) AND</p> <p>(econom* OR ("co-benefit*" AND (beauty</p>	<p>11/6/2023</p> <p>19 results</p> <p>*Does not include geographic terms</p>

	<p>OR food OR health)) OR biodivers* OR "coastal resilien*" OR (erosion AND coast*) OR (coast* AND protec*) OR touris* OR recreation*)</p> <p>*search in Document Title OR All summary text</p>	
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## Key Expert Interview List

<b>Interviewee Name</b>	<b>Organization</b>
Lori Bennear	Duke University
Tim Johnson	Duke University
John Virdin	Duke University, Nicholas Institute
Vincent Doumeizel	Global Seaweed Coalition
Magni Þór Geirsson	<u>ÍslandsPari</u>
Dr. Aaron Eger	Kelp Forest Alliance
Jean-Baptiste Thomas	KTH Royal Institute of Technology
Siggi Pétursson	Lava Seaweed
<i>Pet Care Expert 1</i>	<i>International Pet Care Company 1 [Anonymized]</i>
<i>Pet Care Expert 2</i>	<i>International Pet Care Company 1 [Anonymized]</i>
Mark Smith	Pacific Seaweed Industry Association
John Smet	Pacific Kelp Co.
Nick Stern	Pacific Kelp Co.
Mackenzie Audino	Running Tide
Margret Ormslev Ásgeirsdóttir	Transition Labs
Brian Tsuyoshi Takeda	Urchinomics
<i>NGO Expert 1</i>	<i>International NGO 1 [Anonymized]</i>

## Geospatial Analysis Process

**Key Research Question:** Where are potential project sites for growing kelp (brown algae) in Iceland?

**Output:** Map of potential site extent for MP

### Environmental Characteristics of Species Habitat: Brown Algae (kelp)

Characteristic	Kelp Specifications	Process Steps	Data Source
pH	7–9 <sup>clii,cliii</sup>	1. Download from Bio-ORACLE Website 2. Convert to raster 3. Clip to Iceland EEZ extent 4. Raster calculator for potential aquaculture site map	<a href="#">Bio-ORACLE</a>  <a href="#">Global Ocean data - Copernicus</a> (degraded)
Temperature	between 42-72 degrees F (5.56 – 22.22 Celcius) <sup>cliv</sup>		
Phosphate availability	0.38 to 1.04 mol m <sup>-3</sup> <sup>clv</sup> (phosphate)		
Nitrate availability	0.57 to 11.8 mol m <sup>-3</sup> (nitrate) <sup>clvi</sup>		
Salinity	27.2 to 34.2 <sup>clvii</sup>		
Existing habitat (Depth)	<30m	1. Download from Bio-ORACLE website 2. Convert to raster 3. Clip to Iceland EEZ extent 4. Run raster for <30m depth	<a href="#">Bio-ORACLE</a>  <a href="#">Nordic Kelp Dataset</a> from the <a href="#">Nordic Blue Carbon project</a>
Overlay existing protected areas	Within Iceland EEZ	1. Download WDPA MPA 2. Clip to Iceland EEZ extent	<a href="#">WDPA Marine Protected Areas</a>  <a href="#">Iceland's Marine Protected Areas</a>
Boundary extent	Within Iceland EEZ	1. Import Iceland EEZ extent 2. Transform to Raster	<a href="#">World Exclusive Economic Zones Data Layer (ArcGIS)</a>  <a href="#">Iceland EEZ</a>

### Potential Aquaculture Sites Raster Calculator Equation:

```
(“po4” => 0.38) & (“po4” =< 1.04) &
(“no3” => 0.57) & (“no3” =< 11.8) &
(“temp” => 5.56) & (“temp” =< 22.22) &
(“pH” => 7) & (“pH” =< 9)
```

## Major Iceland Macroalgae Producers

FIGURE 7.6: KEY PRODUCERS IN ICELAND FOR MACROALGAE<sup>362</sup>



Source: [https://www.stjornarradid.is/library/02-Rit--skyrslur-og-skrar/The%20State%20and%20Future%20of%20Aquaculture%20in%20Iceland%20\(1\).pdf](https://www.stjornarradid.is/library/02-Rit--skyrslur-og-skrar/The%20State%20and%20Future%20of%20Aquaculture%20in%20Iceland%20(1).pdf)

## Brown Algae Species List

- *Alaria esculenta* (Dabberlocks, Wing Kelp, Murlins)
- *Ascophyllum nodosum* (Asco, Sea Whistle, Bladderwrack)
- *Asperococcus fistulosus*
- *Asperococcus bullosus*
- *Bifurcaria bifurcata* (Brown Tuning Fork Weed; Brown Forking Weed)
- *Carpomitra costata*
- *Chorda filum* (Dead Man's Bootlaces)
- *Cladostephus spongiosus*
- *Colpomenia peregrina* (Oyster Thief)
- *Cystoseira baccata* (Bushy Berry Wrack) (see *Gongolaria baccata*)
- *Cystoseira nodicaulis* (Rainbow Wrack) (see *Gongolaria nodicaulis*)
- *Cystoseira tamariscifolia* (Bushy Rainbow Wrack) now *Ericaria selaginoides*
- *Desmarestia aculeata*
- *Dictyopteris polypodioides*
- *Dictyota dichotoma*
- *Elachista fucicola*
- *Elachista scutulata*
- *Ericaria selaginoides* (Bushy Rainbow Wrack)
- *Eudesme virescens*
- *Fucus ceranoides* (Horned Wrack; Estuary Wrack)
- *Fucus macroguiryi* (Guiry's Big Wrack)
- *Fucus serratus* (Serrated Wrack)
- *Fucus spiralis* (Spiralled Wrack)
- *Fucus vesiculosus* (Bladderwrack)
- *Gongolaria baccata* (Bushy Berry Wrack)
- *Gongolaria nodicaulis* (Rainbow Wrack)
- *Halidrys siliquosa* (Podweed, Sea Oak)
- *Himanthalia elongata* (Thongweed, Buttonweed, Sea Sphagetti)
- *Laminaria digitata* (Kelp)
- *Laminaria hyperborea* (Forest Kelp, May Weed)
- *Laminaria ochroleuca* (Golden Kelp)
- *Leathesia marina* (Punctured Ball Weed)
- *Litosiphon pusillus*
- *Mesogloia vermiculata*
- *Myrionema strangulans*
- *Padina pavonia* (Peacock's Tail)
- *Pelvetia canaliculata* (Channeled wrack)
- *Petalonia fascia* (Sea Petals, Broad Leaf Weed)
- *Pseudoralfsia verrucosa* (Brown Limpet Paint)
- *Pylaiella littoralis*
- *Ralfsia verrucosa* (see *Pseudoralfsia verrucosa*)

- *Saccharina latissima* (Sugar Kelp; formerly *Laminaria saccharina*)
- *Saccorhiza polyschides* (Furbelows, Furbellows, Sea Hedgehog)
- *Sargassum muticum* (Japweed, an alien species in Europe)
- *Scytosiphon lomentaria*
- *Spermatocnus paradoxus*
- *Sphacelaria cirrosa*
- *Spongonema tomentosum*
- *Stragularia clavata*
- *Stypocaulon scoparium*
- *Taonia atomaria*
- *Undaria pinantifida* (Wakame)

Source: <https://www.seaweed.ie/descriptions/>

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