SUBNATIONAL CLIMATE FUND

PRE-FEASIBILITY STUDY

Global South Seaweed Market Study

Acknowledgements

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Executive Summary

Seaweed is increasingly recognized as a transformative crop addressing various socio-economic and environmental challenges. Cultivating seaweed can be crucial in restoring marine ecosystems, supporting sustainable livelihoods, and supplying raw materials to diverse industries. In the Global South, coastal communities already benefit from seaweed supply chains but stand to gain significantly by harnessing more of seaweed farming's economic potential.

Various recent assessments have outlined potential emerging markets for seaweed biomass—these range from novel agri-inputs to nutraceuticals and carbon sequestration applications. Nevertheless, questions remain regarding the infrastructure and investments needed to drive growth for these applications in the Global South—particularly where progress has been slower than anticipated. In addition, market access and awareness is a persistent challenge in this region, requiring a nuanced understanding of how to navigate emerging markets effectively.

This report assesses new and emerging market opportunities for tropical seaweed in the Global South, focusing on two primary applications in Southeast Asia and the Caribbean:

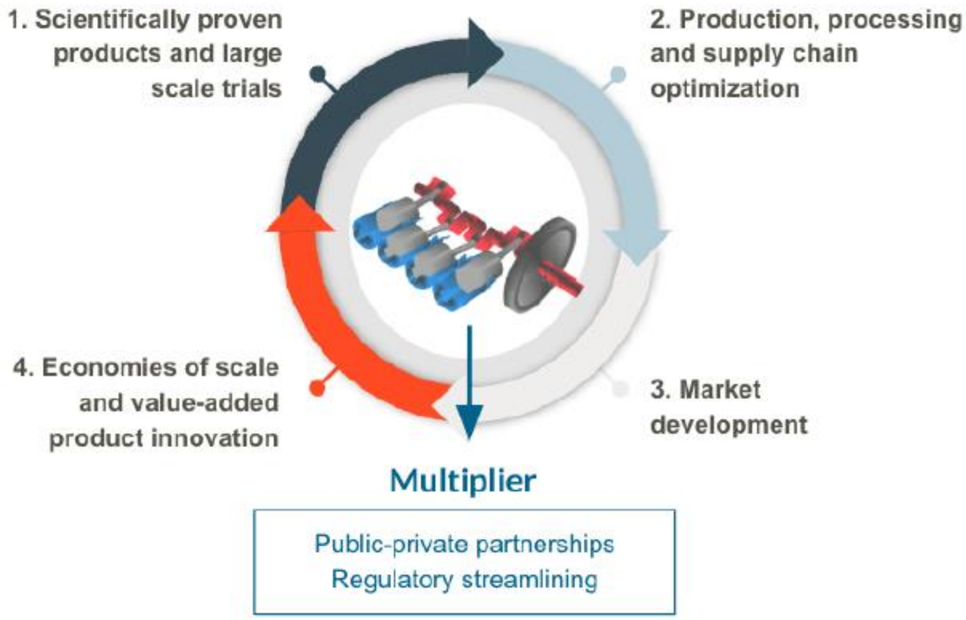
1. Biostimulants: Seaweed products that enhance plant growth and resilience against abiotic stressors in agriculture.
2. Biofuels: Sustainable energy sources derived from seaweed as a third-generation feedstock.

Key Findings

Biostimulants: The global biostimulant market is up-and-coming due to the growing emphasis on sustainable farming practices that support soil health in a changing climate. With scientific evidence indicating the efficacy of tropical-farmed and blooming seaweeds in this context, there is a significant opportunity to build on the strong market presence of wild-harvested seaweed products in the biostimulants sector.

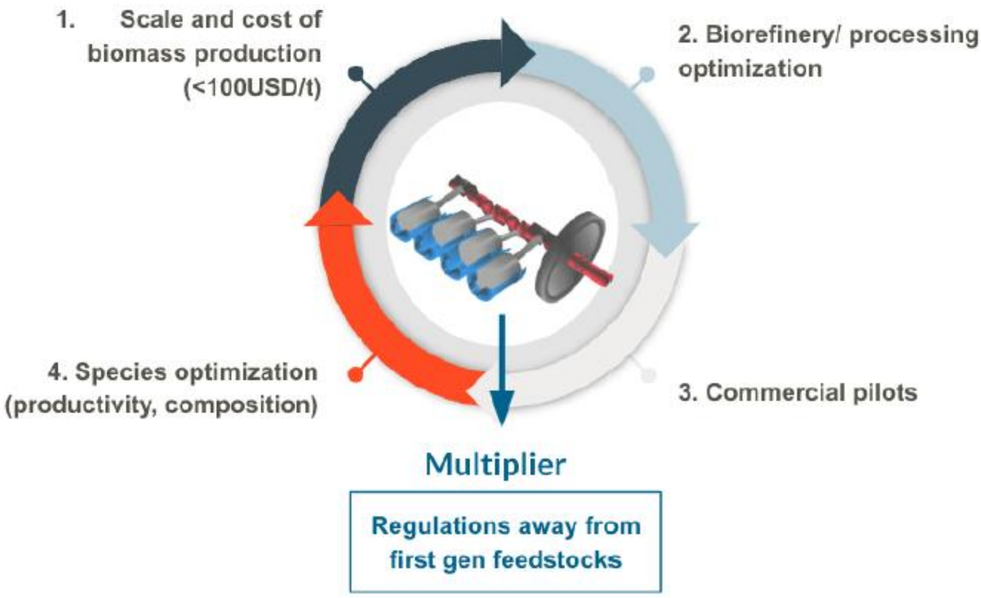
To accelerate the market for novel seaweed-based biostimulants in emerging regions, this analysis points to the following key investment areas in priority:

1. Building the scientific evidence base on the efficacy of products (large crop trials),
2. Optimizing supply chain efficiency (processing),
3. Facilitating awareness and engagement campaigns to animate agri-chem, farming, and regulatory bodies to accelerate market acceptance and compliance,
4. Increase production to lower costs and develop targeted products for more crops and conditions



Biofuels: The market drivers for the biofuel industry are also favorable, with a growing focus on decarbonizing energy sectors. Seaweed can be converted into biofuels using various processing technologies successfully tested at pilot scales.

The commercial viability of seaweed-based biofuels largely depends on advancements in cultivation, harvesting, and increased biomass availability. While technically feasible, the current scenario of seaweed cultivation cannot achieve the scale, production efficiency, and production costs required for supporting a seaweed-based biofuels sector in the near to mid-term. Developing integrated processing facilities for diverse products, investing in commercial pilots, and enhancing research on resilient seaweed strains could accelerate the biofuel opportunity.



Conclusion

The seaweed sector presents opportunities for sustainable development in Southeast Asia and the Caribbean. There is potential for investors like SCF to play a pivotal role by facilitating investments in product trials and R&D, processing infrastructure development, and awareness-building initiatives to support this emerging sector's growth.

1. Introduction

Seaweed farming continues to emerge globally as a sustainable solution to various environmental and social challenges, aligning with multiple UN Sustainable Development Goals. It offers many potential benefits across food security, climate change mitigation, human health, eutrophication reduction, poverty alleviation, and gender equality. Traditionally concentrated in East and Southeast Asia, seaweed cultivation is now expanding worldwide as a pathway towards lower-carbon value chains and sustainable use of coastal waters.[i]

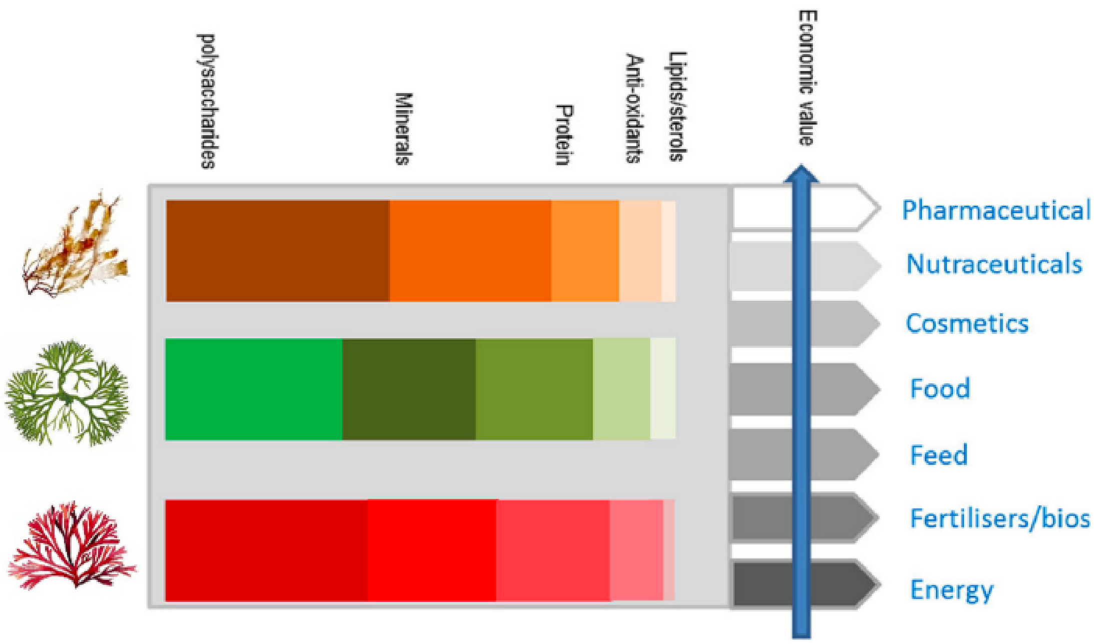
Seaweeds, classified into red, green, and brown types, are rich in essential vitamins, minerals, and valuable bioactive compounds—some of which are unique (fucoidan, alginate, ulvan, carrageenan, agars) and not available in terrestrial crops. The chemical composition and compounds vary by species and environmental factors, meaning seaweeds can service a wide range of different applications.[ii]

Current Seaweed Markets

The majority of farmed seaweed globally is used in the following three sectors:

- **Food** where it is valued for its nutrient density and unique flavors, especially in Asian cuisines.
- **Animal Feed** as whole feed and feed ingredients for aquaculture species like abalone, oysters, and sea urchins.
- **Hydrocolloids**, as a source of alginate, agar, and carrageenan, are essential gelling, stabilizing, and thickening agents in food and other products.

Figure 1: Macroalgae biomass composition, valorization routes and relative economic value (Adapted from Torres et al (2019)[iii]



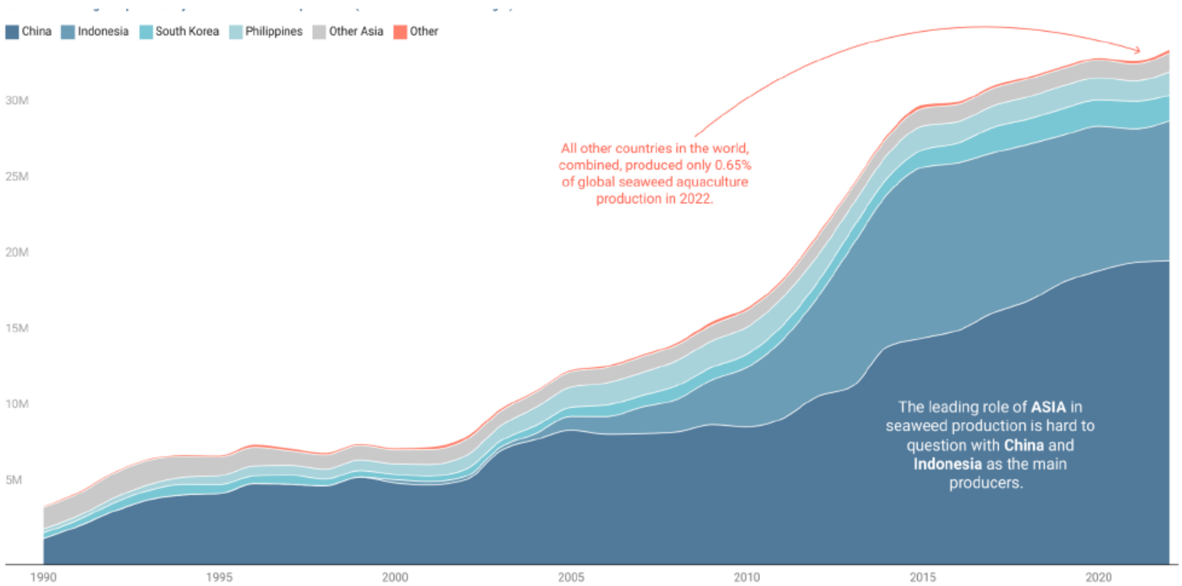
Many additional applications for farmed seaweed have varying degrees of adoption, from biostimulants to biofuels and bioplastics. Despite the high potential to bolster the resilience and economies of remote coastal communities, these seaweed applications still lag behind the main three in terms of market implementation.

1.1. The current state of seaweed production

Almost all seaweed supply comes from aquaculture, primarily produced in land-based ponds and nearshore systems, dominated by only a handful of seaweed species groups. Production volumes have tripled over the past two decades - with commercial seaweed aquaculture beginning only 50 years ago. As wild seaweed resources approach their sustainable harvesting limits, future growth in the industry increasingly depends on aquaculture. According to the latest State of World Fisheries and Aquaculture (SOFIA) report from the Food and Agriculture Organization of the United Nations (FAO), total global algae production reached 36 million tonnes (wet weight) in 2022, encompassing both wild-harvested and farmed seaweed.[iv]

Global seaweed production is highly concentrated, with 99% of farmed seaweed originating from a few East and Southeast Asian countries; China and Indonesia alone account for 56% and 27%, respectively. However, recent on-the-ground analyses indicate that official production figures from several major producing countries may be overreported, suggesting that global production volumes could be lower than previously estimated.

Figure 2: Global seaweed production volumes in tonnes wet weight 1990-2022 by country



(Chart by Hatch Innovation Services, based on 2022 production figures provided by FAO Fisheries and Aquaculture)

While farmed production may be concentrated in China and Southeast Asia, other regions with abundant stocks of wild seaweed aggregate in large algae blooms. Noting that these stocks could also serve as new biomass sources for underdeveloped supply chains, this report focuses on the opportunities and challenges facing tropical seaweeds and sargassum macroalgae across Latin America, the Caribbean, and Southeast Asia. This report seeks to inform investors about growth opportunities in these areas.

1.1.1. Current Status of the Tropical Red Seaweed Sector

Eucheumatoids, the most prominent group of farmed tropical red seaweeds (Rhodophyta) today, began to be commercially cultivated in the 1970s in the Philippines. *Kappaphycus alvarezii* and *Eucheuma denticulatum* are the primary species farmed for carrageenan extraction—a globally traded product valued for its gelling, thickening, and stabilizing properties in the food, pharmaceutical, cosmetics, and nutraceutical industries. Due to similar cultivation methods and interchangeable use of these species, they are collectively referred to as eucheumatoids. The eucheumatoid industry is a key income source for hundreds of thousands of smallholder farmers in economically disadvantaged coastal areas, particularly in the Coral Triangle (Indonesia, the Philippines, Malaysia) and Tanzania. Interest in seaweed farming is also growing across Africa and Latin America, with over 30 countries now involved in eucheumatoid production. However, primary production remains centered in the Coral Triangle, supported by a close-knit network of value chain actors.[v] [vi]

Despite increased demand, eucheumatoid production has declined in key regions. Continuous cloning reduces genetic diversity, making strains vulnerable to diseases. Farmers lack access to healthy seedlings, leading to lower yields. Diseases, including "ice-ice," have spread through infected seedlings, worsening crop quality. Climate change raises sea temperatures, negatively affecting the growth and quality of tropical seaweeds.[vii]

Gracilaria is the second most farmed tropical seaweed. It is responsible for over 90% of the global production of agar, a hydrocolloid with multiple uses in the food, pharmaceutical, and cosmetic industries, including as a gelling agent, thickener, stabilizer, and emulsifying agent.

1.1.2. Current Status of Sargassum

Sargassum, a brown macroalgae, has emerged as a significant environmental and economic issue for the Caribbean since 2011, with mass bloom events—known as Sargassum events—becoming increasingly common(estimated at 25 Mio MT wet weight). These events have severe impacts on coastal ecosystems and local economies. Decomposing Sargassum on beaches releases harmful gases, such as hydrogen sulfide, and creates anaerobic conditions that disrupt marine life. The tourism industry suffers from the unattractive appearance and odor, while the fishing industry is hindered due to the disruption of fishing activities and decreased catches.[viii]

The increase in Sargassum blooms is linked to nutrient enrichment from agricultural runoff and waste, rising sea temperatures caused by climate change, and changes in ocean currents that transport the algae from the Sargasso Sea to coastal areas. The precise mechanisms driving these events are still not fully understood despite extensive research.

Efforts to address this issue include developing remote sensing technologies to monitor and predict Sargassum influxes and implementing offshore collection to prevent coastal accumulation. Venture-backed startups and research teams are developing ways to collect biomass before it reaches the coastlines safely and exploring the most efficient ways to transport and process it. The valorization of Sargassum biomass into biofuels, fertilizers, and other products shows potential but requires further exploration due to challenges like heavy metal contamination and inconsistent supply. Collaborative strategies involving governments, researchers, and local communities are essential to mitigate impacts and transform this environmental challenge into an economic opportunity.[ix] [x]

1.1.3. Key Supply Chain Challenges for Seaweed

Ensuring a stable and efficient supply chain is vital for successfully scaling the seaweed sector in the Global South. As the industry strives to meet the growing demand for applications such as biostimulants, animal feed additives, and bioplastics, it faces two core challenges: fragmented supply chains and variability in quality-controlled raw material availability.

The fragmented supply chain in tropical seaweed production and processing presents a significant challenge. These types of seaweed, particularly Eucheumatoids and Gracilaria species, are primarily cultivated by smallholder farmers across often remote coastal areas. After harvest, the wet seaweed is typically sundried before being sold to local aggregators and then transported long distances over roads or maritime routes to reach processing centers. Inadequate drying conditions cause seaweed to lose its quality. Investing in improved stabilization techniques—such as modular drying stations, fermentation sites, or ensiling platforms where sun-drying is impractical—located close to production areas will greatly improve this situation. By stabilizing biomass immediately after harvest, producers can preserve critical bioactive compounds, reduce microbial spoilage, and lower transportation costs by decreasing water weight.

Another central issue lies in the variable nature of raw seaweed biomass. Seasonal shifts, genetic differences among strains, and fluctuating oceanic conditions influence the seaweed's composition. Inconsistencies in moisture content, bioactive compounds, and purity levels undermine the predictability required by industrial processors who depend on uniform inputs.

Without commonly accepted quality standards, each transaction may involve renegotiations over quality metrics. The absence of clear benchmarks leads to misunderstandings and discourages long-term contracting. Establishing unified quality benchmarks for moisture content and bioactive compound thresholds is a crucial pathway to improvement. This step would help align expectations between producers and buyers, reduce instances of disputed shipments, and enhance overall market transparency. Producers can adopt cultivation and initial post-harvest techniques that consistently deliver the desired quality specifications when they know the expected quality parameters. Processors, in turn, gain the confidence needed to secure regular supply agreements, minimizing uncertainty and transaction costs.[xi]

2. Market Analysis - Seaweed-based Biostimulants

2.1. Introduction to Biostimulants and Rationale

Seaweed-based agri-inputs have been gaining momentum in crop production systems in the past 30 years, owing to their unique bioactive components and positive effects when used as biofertilizers, liming materials, soil improvers, plant biostimulants, and fertilizing product blends.[xii] Biostimulants in particular, have been gaining traction as agricultural inputs. These products mitigate abiotic stress and enhance plant productivity through increased biological activity. They can be applied to maintain or increase crop yields and quality and reduce fertilizer usage. In recent years, the impact of synthetic fertilizers on soil quality has gained growing attention in the agriculture sector and resulted in a wider interest in biological alternatives. Significant drivers are increasing the use of biostimulants – both as a replacement or supplement to conventional fertilizers. For example, abiotic stressors, including excessive heat and droughts, are increasing in critical agricultural markets. Biostimulants offer a low-cost solution to reduce the impacts of these events and are being implemented across agriculture, horticulture, and ornamental plants sectors.[xiii]

2.2. The Biostimulant Market

The shift away from inorganic fertilizers has sparked growing interest in biostimulants, mainly due to the environmental pressures traditional agriculture faces from climate change, land scarcity, and biodiversity loss. Rising consumer demand for organic foods, supportive policies, government subsidies, and research initiatives further accelerate this growth. In addition, the recent spike in fertilizer prices, influenced by geopolitical factors and rising energy costs, has also accelerated the shift to biostimulants, which offer growers a cost-effective and efficient alternative.

According to industry leaders like David Iglesias of Biorizon Biotech, biostimulants are becoming indispensable for managing environmental stress. Although biostimulants represent a relatively small segment of global agriculture, their sales have surged over the past two decades, driven by population growth, innovative products, and greater awareness among growers.

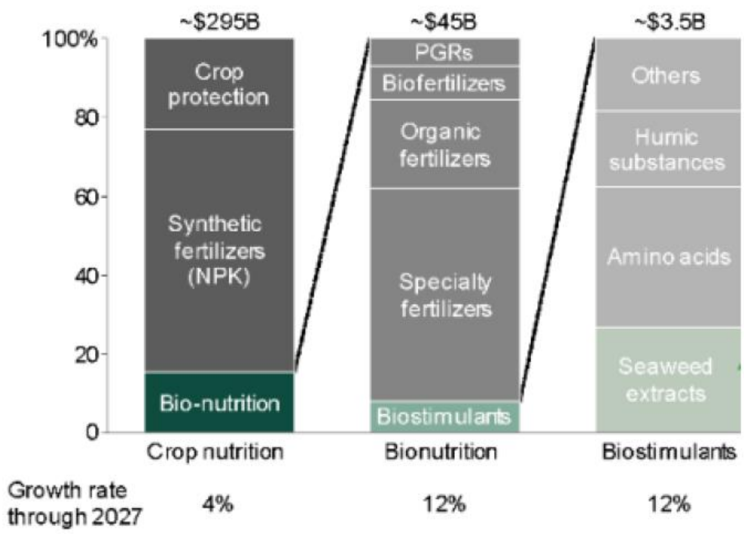


Figure 3: *Global crop nutrition and biostimulant markets, 2022 ($B) by The Nature Conservancy*[xiv]

The seaweed biostimulants market, valued at around $1.2 billion, represents a small segment of the broader $300 billion crop nutrition market. However, it is expected to grow consistently at a compound annual growth rate (CAGR) of 12% through 2027. If projections hold true, the seaweed market could reach a value of $2.5 billion by 2030, with around 1% of global farmland being treated. However, it is important to note that most commercial products currently rely on wild-harvested seaweed rather than cultivated varieties.[xv]

Biostimulants sourced from wild-harvested seaweeds have established a market niche, aiming to replicate this success with products derived from cultivated seaweeds. In tropical regions, the focus shifts to adding value; biostimulants are priced higher than carrageenan, promoting revenue diversification and minimizing risks associated with market consolidation. Island nations in the Caribbean, Indian Ocean, and Pacific aim to exploit seaweed biostimulants to capitalize on harmful algal blooms. Additionally, nonprofit organizations value seaweed biostimulants for their potential to decrease dependence on conventional fertilizers and their related carbon emissions.[xvi]

Various seaweed species offer a rich concentration of bioactive compounds such as plant hormones, amino acids, and other essential bio-actives for plant growth. Some organizations have developed efficient extraction processes primarily using wild-harvested species such as *Ascophyllum nodosum,* which accounts for over 90% of the biomass used in the biostimulant industry. These biostimulants are offered in both liquid and dry forms and are typically applied to crops through foliar sprays—where they are directly applied to leaves—or drip irrigation, delivering them to the soil. In contrast, few biostimulants derived from farmed seaweed species have successfully scaled to commercially relevant levels.

In the short term, expansion is expected to rely on established wild-harvested cold-water species. The Nature Conservancy estimates that meeting demand until 2027 will require about 700,000 tons of wet seaweed, primarily sourced from wild harvesting in Norway, South Africa, Chile, and New Zealand. Environmental pressures and limited wild stock capacities are also prompting a shift toward farmed seaweed to ensure stable supply chains.

Long-term growth will likely come from farmed seaweed and algal blooms, though challenges like stable biomass availability, consistent quality, and cost-effectiveness remain. Labor-intensive processes keep costs high, requiring economies of scale and automation for large-scale production. While wild harvesting can be cheaper, it is not enough to meet demand, and many regions limit harvests to maintain sustainability. Companies are increasingly investing in seaweed farming to secure a sustainable and consistent supply for the growing biostimulant market, with the anticipated demand potentially stimulating seaweed farming industries outside of Asia, if current challenges can be addressed.

2.3. Seaweed as biostimulants

2.3.1. Seaweed Value Proposition

Seaweed extracts have been a core part of the biostimulants market, with a long tradition of use in some agricultural economies because of their ability to increase crop resistance to adverse environmental factors such as drought, salinity, and extreme temperatures, as well as resistance to oxidative stress, owing to the presence of plant growth hormones such as auxins and cytokinins.[xvii] It has also been reported that seaweed extract can enhance plants' disease-resistance properties.[xviii] Furthermore, using seaweed extracts has been linked to improved water-holding capacity and improved microbial soil communities. Consequently, applying seaweed biostimulants, and the accompanying potential benefits for soil and plants, can enhance production yields.[xix]

Seaweed-based biostimulants offer additional environmental benefits, enhancing their value as a sustainable agricultural solution. Seaweed biostimulants have a lower environmental impact compared to synthetic fertilizers. Initial agricultural trials indicate that seaweed biostimulants can reduce CO2 emissions by approximately 50% per application compared to the application of synthetic fertilizer.[xx] Additionally, biostimulants can increase soil carbon and nitrogen levels, potentially acting as a soil carbon sequestration tool.[xxi]

2.3.2. Alignment with the Sustainable Development Goals

Seaweed farming aligns with global sustainability goals, including those set by the United Nations. As the world seeks to reduce greenhouse gas emissions, seaweed presents a promising pathway toward achieving these objectives while supporting local economies.

2 ZERO HUNGER — Seaweed biostimulants improve crop yields and resilience, supporting food security, especially in regions like Latin America and Southeast Asia, where agriculture is crucial for maintaining the population.

5 GENDER EQUALITY — Seaweed farming provides income and financial stability for women worldwide, strengthening their economic independence in target regions.

8 DECENT WORK AND ECONOMIC GROWTH — Seaweed farming and biostimulant production create sustainable jobs in coastal communities, supporting local employment and international trade as global demand for eco-friendly agriculture grows.

12 RESPONSIBLE CONSUMPTION AND PRODUCTION — As natural alternatives to synthetic fertilizers, seaweed biostimulants reduce nutrient runoff and harmful chemicals, fostering cleaner and more sustainable farming.

14 LIFE BELOW WATER — Seaweed farming contributes to regenerative ocean practices, reducing acidification and enhancing marine biodiversity, particularly in Southeast Asia's coastal areas.

15 LIFE ON LAND — Seaweed biostimulants improve soil health band oost fertility, water retention, and biodiversity, addressing soil degradation issues in Latin American agriculture.

2.3.3. Technology Status

The TRL for wild seaweed species is high. Still, few, if any, biostimulants derived from farmed seaweed species have successfully scaled manufacturing, so the Technology Readiness Level (TRL) is likely around 7-8. Manufacturers of seaweed biostimulants tend to develop proprietary extraction methods and blends of different seaweed species, aiming at differentiating their products and ensuring product stability and quality. These include various extraction methods such as hydrolysis, alkaline or acidic extraction, and fermentation, with the most common process involving heating the seaweed in alkaline sodium or potassium solutions.

Advanced extraction techniques such as ultrasound-assisted extraction (UAE), enzyme-assisted extraction (EAE), supercritical fluid extraction (SFE), microwave-assisted extraction (MAE), and pressurized liquid extraction (PLE) offer advantages over conventional methods.[xxii] These techniques preserve the activity of bioactive compounds better, increase extraction yield, reduce extraction time, and are more environmentally friendly as they avoid using toxic solvents. Nevertheless, applying these technologies to most farmed seaweed species is still in the early stages.

i. Technology Bottlenecks

Substantial scientific and anecdotal evidence has shown that seaweed biostimulants improve plant health, stress tolerance, and crop yields - yet consistent performance in the field has been challenging. The wide variability and variety of chemical compounds available in a seaweed extract and the variability in interactions with different plants and soil types have historically led to inconsistent performance. Additionally, a lack of standards means it is difficult to compare products, which has opened the door for certain products with questionable efficacy - e.g. some Asian products might not even contain the seaweeds mentioned on the label.

Ensuring consistent product quality and efficacy is challenging, given variations in seaweed growth conditions, extraction methods and application. Seasonal variability, growth conditions of the seaweed and its genetics affect its composition. Since a lot of biostimulant products are blends derived from different seaweed, it is often challenging to understand the percentage content of key active compounds (such as laminarin, fucoidan, and mannitol) that are available. Furthermore, extraction methods change according to the compounds available and can significantly influence the yield and effectiveness of the desired compounds. In addition, the effectiveness of the biostimulant product also varies depending on the targeted crop and soil conditions. Such variability and perishability of the seaweed as a raw material often result in fluctuating input quality for downstream applications, thereby complicating the efforts of processors who require stable, uniform materials to ensure standardized product outputs. The lack of widely recognized quality benchmarks or industry standards further exacerbates this challenge. Without shared criteria for assessing key attributes, producers, processors, and buyers may rely on assumptions of what constitutes “high-quality” seaweed, leading to conflicting expectations, inefficiencies, and difficulties in securing long-term, reliable supply arrangements.[xxiii]

Another major hurdle is the lengthy development time necessary to introduce new products to the market. It typically takes several years to establish the scientific basis for these products and prove their efficacy through field trials.

ii. R&D Needs

More research is needed to identify and quantify the active compounds in seaweed biomass that contribute to their biostimulant properties and how these bioactive compounds interact. These compounds are not species-specific and often act synergistically, which complicates identifying whether a single compound or a group of compounds is responsible for the desired agricultural effects. It is, therefore often difficult to identify a specific mode of action (MOA) in the soil. Prominent wild-harvested species like Ascophyllum nodosum have more extensive documentation regarding the effectiveness of their bioactive compounds. In contrast, farmed seaweed species are relatively new to biostimulant products, resulting in a lack of data on the available compounds and efficacy on different crop and soil types.

A further complication in understanding the mode of action is the variability in application. This is true for all biostimulants. Whether a product should be applied as a foliar spray or in a powdered form in conjunction with weather conditions depends on the increasing use of data analytics and crop monitoring devices. Progress has been made in crop monitoring and agronomic sophistication. Still, the fastest way to prove efficacy would be to start with standardization and homogenization of the seaweed-based biostimulants themselves – that is, understanding what percentage content of key biostimulant chemicals (such as laminarin, fucoidan, and mannitol) exist in a given product.[xxiv] Extensive field trials are needed to provide solid data on efficacy and benefits across different crops and conditions, including carbon emissions and LCA benefits - key purchasing drivers for major agri-chem and corporate buyers.

iii. Scalability

The distance the biomass has to travel to be processed can heavily influence the quality and cost of production. Biostimulants can be produced directly using both wet seaweed or dry seaweed. Most established biostimulant manufacturers have developed processing plants close to the shoreline in their main market to take advantage of using wet biomass. For others, sourcing biomass from other countries or regions in a stabilized condition (dried or fermented) is oftentimes necessary but also adds logistical costs. This logistical strain is compounded by the short shelf-life and rapid perishability of fresh seaweed; without stbilizing or processing, microbial growth and enzymatic activity can degrade both nutritional and functional properties of the biomass.[xxv]

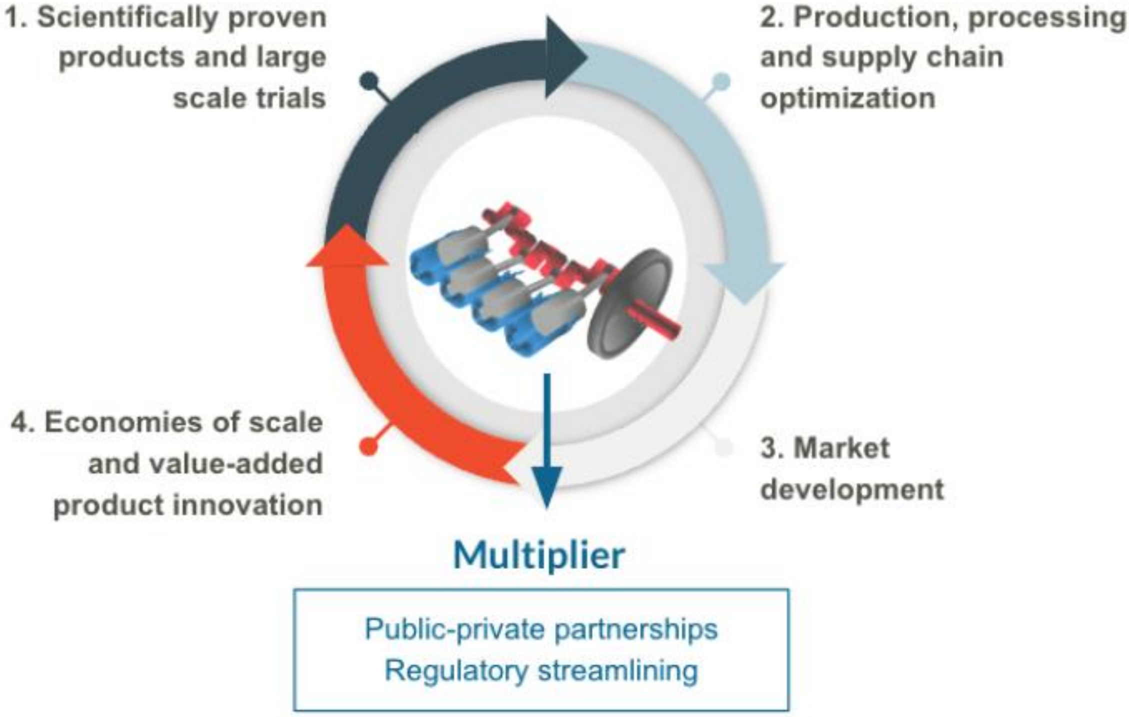
This stabilisation step is often recognized as one of the key areas to deploy capital to optimize the process for biostimulant production from emerging seaweed farming regions. Some companies are developing novel approaches with close loop systems, where seaweed is used to filter wastewater of the aquaculture operation, and the harvested biomass is turned into liquid biostimulant.

2.4. Investment opportunities

2.4.1. Overview of key investment area

Targeted investment in infrastructure, R&D, and market development will be important for enabling large-scale production and adoption of biostimulants. The following key areas highlight critical investments needed to enhance the value chain and ensure scalable, economically viable production.

Figure 5: Flywheel: What could enhance the value chain for scaling biostimulants sourced from cultivated seaweed?



1. Developing effective seaweed-based biostimulants in Southeast Asia and the Caribbean requires **additional scientific research to validate formulations** that improve plant growth and stress resilience. On the macro level, this involves conducting and supporting more large-scale trials across various crops, soil types, and climates, which can demonstrate product efficacy and support tailored applications. On the micro-level, R&D should also focus on understanding the molecular modes of action and mechanisms of these novel seaweed species extracts, which can enable more targeted formulations and expand performance metrics to include soil health indicators. Integrating soil microbiome data into product development could further support customized solutions for diverse regional needs.
2. To scale effectively, there is a need to **establish and optimize facilities for efficient seaweed extraction and processing.** Investing in technologies that maximize yield while reducing environmental impact can enhance profitability and sustainability. Regarding stabilization and shipping, innovations that retain bioactivity in powdered forms could also reduce shipping costs and make distribution more economical. Investing in stabilization is often cited as a critical unlock for this sector. Optimizing logistics and distribution networks will improve market accessibility, ensuring farmers receive timely access to biostimulant products, which is key for widespread adoption. This process should first map the market opportunity in detail by the nation to optimize for site selection for biorefinery location.
3. **Market Development by raising awareness and educating agricultural stakeholders about the benefits of seaweed-based biostimulants will support market penetration.** Targeted educational campaigns can foster acceptance among farmers, agronomists, and others in the agricultural community, emphasizing the role of biostimulants in sustainable farming.

4. **Scaling production and processing to achieve economies of scale** will be a primary factor in reducing costs per unit and making them more accessible for application on commodity-type crops. The first step in this process could involve completing a general cost assessment of available processes and exploring the pricing elasticity for any potential new or replacement product in this market. Improved extraction techniques with higher yields and larger production volumes will help make seaweed biostimulants more affordable, which allows the development of targeted products to lower value agricultural crops and, in turn, can **enable more widespread adoption.** Additionally, exploring value-added products from seaweed processing by-products presents opportunities to offset costs and increase profitability.

Flywheel multipliers

Beyond these core investment areas, several catalysts will support the acceleration of the flywheel. Two critical areas include:

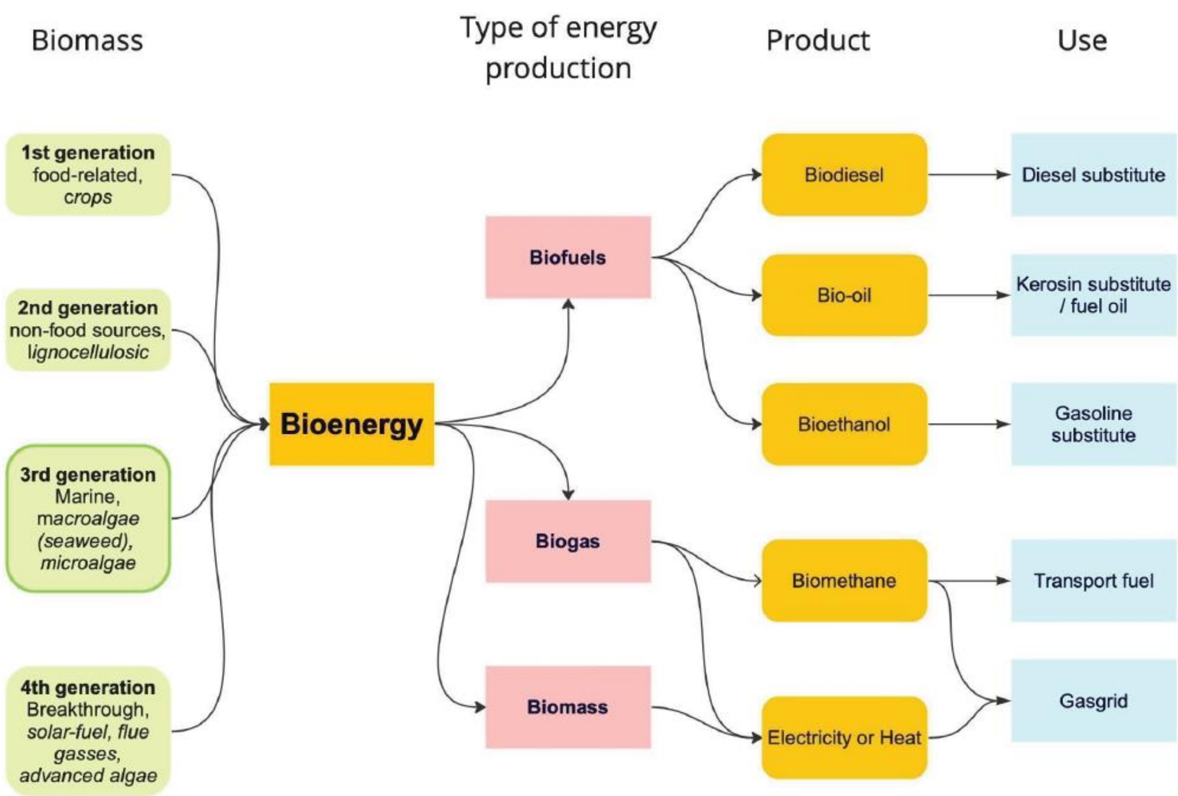
1. **Validation of sustainability metrics.** Responsible farming practices and monitoring are essential to ensuring the long-term availability of seaweed resources. Life Cycle Assessments (LCAs) are valuable for quantifying the environmental benefits of seaweed-based biostimulants over synthetic alternatives. They provide data-driven evidence that can appeal to eco-conscious customers pursuing net-zero targets and regulatory bodies alike.
2. **Regulatory engagement and streamlining.** By working with authorities to navigate and shape the legal landscape with more explicit definitions and guidelines, companies can advocate for policies that support seaweed-based products. This may involve expanding the definition of biostimulants or exploring alternative regulatory categories to facilitate smoother market entry. A risk in this space is avoiding 'snake oil' products that come on the market and blemish the name of biostimulants.

3. Market Analysis - Seaweed-derived biofuels

3.1. Introduction to Biofuels and Rationale

Biofuels are renewable energy sources derived from biological materials, including plants, animal waste, and organic matter. Unlike fossil fuels, which require millions of years to form from ancient organic materials, biofuels can be produced relatively quickly, making them a more sustainable option for energy production. The term "biofuels" generally refers to liquid fuels such as ethanol and biodiesel, which serve as alternatives to gasoline and diesel. Liquid fossil fuel represents about one-third of global energy consumption. Biofuels are liquid fuels, bioethanol, and bio-diesel derived from living or once-living organisms (biomass). Additionally, biofuels encompass gaseous energy forms like biogas and hydrogen produced from renewable sources.[xxvi]

Figure 6: Overview of biomass categories and bioenergy product and use cases



Biofuels are typically categorized by their biomass sources

- **First-generation biofuels** use food crops like corn, sugarcane, and soybeans. Ethanol is made from fermented sugars and starches, while biodiesel is produced from oils and fats. Although these biofuels are renewable, they compete with food production and can impact land use.
- **Second-generation biofuels** are made from non-food biomass, such as agricultural residues (e.g., straw), woody materials, and other plant-based waste. These biofuels use advanced technologies like gasification and pyrolysis to convert complex plant matter into fuel. They offer greater sustainability but have higher production costs and require sophisticated technology.

- **Third-generation biofuels** focus on algae and other microorganisms, which can grow quickly in diverse conditions, including saltwater, without needing arable land. Algae can be converted into bio-oil, offering high yields. The single biggest barrier to market deployment of algae remains the high cost of cultivating the algal biomass feedstocks, currently a factor of 10-20 too high for commodity fuel production.[xxvii] [xxviii]

The idea of using algae as a third-generation biomass for bioenergy is not new. The exploration of algae as a source of biofuels began in earnest during the 1970s when researchers recognized the potential of both microalgae and macroalgae/seaweed to provide renewable energy alternatives. Since then, microalgae have been more extensively tested for biofuel production due to their rapid growth rates and higher oil yields than macroalgae. As a result, seaweed has historically been less focused on biofuel applications but is gaining attention due to its unique advantages. Unlike land-based plant (lignocellulosic) biomass, seaweeds contain higher concentrations of carbohydrates and very little or no lignin content, implying the requirement of a milder pre-treatment process for seaweed-based bioethanol production.

3.2. The Biofuel Market

In 2022, biofuel demand reached a record high, a trend expected to continue as nations pursue net-zero emissions targets. The International Energy Agency (IEA) projects that biofuel production must triple by 2030 to align with global climate objectives.[xxix] Efforts to reduce greenhouse gas emissions and life cycle assessments are accelerating the move toward bioenergy. This anticipated growth is underpinned by national policies and the diversification of feedstocks utilized in biofuel production. The present biofuels market is primarily led by first-generation liquid biofuels—such as bioethanol and biodiesel—sourced from food crops like corn, sugarcane, and vegetable oils.

Growing concerns about sustainability and competing with food production shift focus to the use of non-food biomass, waste materials, and algae. Biomethane production from waste sources—sewage treatment waste, landfill gas, and plant waste like grass cuttings. Biomethane, possessing properties similar to fossil natural gas, can fuel Natural Gas-powered Vehicles (NGVs) or be injected into the natural gas grid. This substitution can supply end-users such as power plants, industries, and households. The European Biogas Association (EBA) projects that biogas could replace 10% of the EU's gas demand by 2030 and up to 30-40% by 2050.

Emerging economies, particularly Brazil, Indonesia, and India, drive new biofuel demand. These countries have rising transportation fuel needs, biofuel blending targets, and abundant domestic feedstocks. Ethanol and biodiesel usage is expanding significantly in these regions. Conversely, advanced economies like the European Union, the United States, Canada, and Japan face volume growth constraints due to increased adoption of electric vehicles (EV), improvements in vehicle efficiency, high biofuel costs, and technical limitations. In these markets, renewable diesel and jet fuel are the primary growth segments.

Regional Dynamics and Key Markets

Region	Status
United States	The U.S. remains a leader in ethanol production, primarily using corn as a feedstock. The Renewable Fuel Standard (RFS) mandates blending biofuels into the national fuel supply, encouraging steady demand for ethanol and biodiesel. Recent policies like the Inflation Reduction Act (IRA) provide further incentives for developing advanced biofuels, which is expected to drive growth in the next decade.
European Union	The EU emphasizes biodiesel production using vegetable and waste oils, with blending mandates and the Renewable Energy Directive II (RED II) promoting renewable energy in transport. Algae is recognized as an advanced feedstock in the EU, with mandates and regulations in key regions suggesting long-term demand growth.
Latin America and the Caribbean	Fossil fuels dominate in many end-use sectors, and oil is notably the primary fuel used in transport in Latin America. However, the share of biofuels in road transport is twice the global average. With further policy support, biogas and biomethane use could also expand in electricity generation and transport. Advanced biofuels have significant potential as an economically competitive export of jet kerosene in this region. As a major ethanol producer, Brazil, for instance, is a prominent producer and consumer of biofuels and leveragessugarcane's high yield to produce biofuel efficiently. The RenovaBio program aims to reduce carbon intensity in transportation fuels through a market-based approach requiring fuel distributors to purchase decarbonization credits (CBIOs) to meet emission reduction targets. This initiative supports the expansion of Brazil's ethanol market and contributes to national climate goals.[xxx]
Southeast Asia	By mid-century, energy demand in Southeast Asia is predicted to overtake the European Union's. India and Indonesia are emerging players in the biofuels market. India has set a target of 20% ethanol blending in gasoline by 2025, supported by increased ethanol production capacity. Indonesia, the largest producer of palm oil-based biodiesel, has implemented a B35 mandate (35% biodiesel blend) to reduce its dependence on oil imports India achieved 10% ethanol blending in 2022, ahead of schedule, in its pursuit of a 20% blending target by 2025. Indonesia is expanding its biodiesel blending target to 35% from 30%, and Brazil is expanding biodiesel blending to 15% by 2026 from 12% in 2023.[xxxi]

The global Sustainable Aviation Fuels (SAFs) market, in particular, requires alternative biofuel solutions. The aviation industry is considered to have fewer alternative solutions to decarbonize since electrification is not yet possible and too few other low-carbon technologies exist for long-haul air transportation. While air traffic is projected to grow globally, the demand for SAFs is expected to increase significantly, not least boosted by respective legislatures. Currently, jet fuel is twice as expensive as methane, making this a potential entry market for new high-cost biofuels.[xxxii]

3.3. Seaweed as a biofuel source

3.3.1. Seaweed Value Proposition

Seaweed's value proposition in the biofuel industry is compelling, showcasing its promise as a sustainable energy alternative that fosters environmental health and economic resilience in coastal communities. Seaweed is acknowledged not only for its low carbon footprint and as a third-generation feedstock, but its environmental advantages are also increasingly recognized, as the alignment with several Sustainable Development Goals (SDG's) indicate. Seaweed farming reduces eutrophication and supports marine ecosystem health by absorbing excess nutrients from coastal waters.

A major benefit of seaweed is its biomass yield and composition. A study by Bellona (2017) suggests that seaweed can grow about 26 tonnes of dry weight per hectare, compared to 2.3 tonnes of soya and 5.1 tonnes of corn. Tropical seaweeds can grow quickly and generate significant amounts of biomass through short farm cycles (up to 45 days) and year-round productivity. Some species, on the other han,d have high carbohydrate levels that can be transformed into biofuels such as bioethanol and biogas. Moreover, seaweed's versatility goes beyond biofuels; it finds applications across various industries, making it a promising candidate for biorefineries that help producers diversify their revenue. Advances in extraction and conversion technologies are enhancing the viability of seaweed-based biofuels. Current research focuses on improving the efficiency of converting seaweed biomass into usable fuels, making it a more competitive choice than fossil fuels.[xxxiii]

3.3.2. Alignment with the Sustainable Development Goals

When undertaken correctly, seaweed farming aligns with global sustainability goals, including those set by the United Nations. As the world seeks to transition away from fossil fuels and reduce greenhouse gas emissions, seaweed presents a promising pathway toward achieving these objectives while supporting local economies.

2 ZERO HUNGER

Seaweed biostimulants improve crop yields and resilience, supporting food security, especially in regions like Latin America and Southeast Asia, where agriculture is crucial for stability and productivity.

5 GENDER EQUALITY

The seaweed sector has been shown to empower women and marginalized groups through their involvement in the value chain, from cultivation to processing and marketing. This participation fosters gender equality and social inclusion in coastal economies.

8 DECENT WORK AND ECONOMIC GROWTH

The seaweed industry can generate new jobs and economic opportunities in coastal communities, particularly in developing countries. By diversifying income sources for small-scale farmers and harvesters, it contributes to sustainable livelihoods and economic resilience.

11 SUSTAINABLE CITIES AND COMMUNITIES

Biofuels from seaweed can reduce reliance on fossil fuels in urban areas, contributing to cleaner air and lower emissions.

13 CLIMATE ACTION

Seaweed farming has significant carbon sequestration potential, helping mitigate climate change. It absorbs CO2 during growth, and when used as biofuel, it can replace fossil fuels, thereby reducing greenhouse gas emissions associated with energy production.

14 LIFE BELOW WATER

Seaweed cultivation supports marine biodiversity by providing habitats for various marine species. Sustainable harvesting practices can help maintain healthy marine ecosystems while promoting the conservation of ocean resources.

15 LIFE ON LAND

Seaweed biostimulants improve soil health, boosting fertility, water retention, and biodiversity, addressing soil degradation issues in Latin American agriculture.

3.3.3. Current State of the Seaweed Biofuel Market

Currently, seaweed biofuel is not commercially produced. The main obstacle is the high cost of generating seaweed biomass and the required volumes. The existing infrastructure for seaweed farming is largely set up for small-scale, manual operations, which creates significant challenges for scaling up to biofuel production. Producing seaweed-based biofuel necessitates large quantities of biomass, in the range of hundreds to thousands of tons, to reach commercial viability. This requirement places substantial logistical and economic demands on producers, who need a reliable and scalable supply of seaweed feedstock.

Biomass availability and cost of production have so far been the major bottleneck to move from research or pilot facilities to commercial operations. Wild harvesting of natural seaweed beds is relatively low cost. However, the available capacity from wild sources in most cases is insufficient to meet the volumes required for bioenergy production and will be difficult to justify given the potential environmental damage wild harvest can create. On the other hand, current systems of cultivation or farming of seaweed are prohibitively expensive for bioenergy applications. The cost of all four operations stages, namely cultivation, harvesting, post-harvest treatments and energy extraction, must be considered. In particular, given the amount of fossil fuel needed during production, the sustainability of using seaweed biofuels is questionable. For large-scale cultivation, the impact on the surrounding ocean ecosystems and nutrient levels have yet to be analyzed more comprehensively to ensure sustainability.[xxxiv]

3.3.4. Funding of Seaweed Biofuel Research

To meet the biomass output required, advanced farming technologies capable of large-scale, off-shore operations and maximum yields per hectare have yet to be developed. One promising strategy is the establishment of submerged seaweed farms, which could overcome the limitations of shallow-water farming and potentially facilitate automation; however, these technologies necessitate considerable R&D investments to become financially and operationally feasible. The funding landscape for biofuel research from macroalgae has expanded significantly, with a notable increase since 2010, driven by government entities and specific research programs across multiple countries.

- U.S. Department of Energy (DOE) - Through programs like ARPA-E, the DOE funds large-scale sustainable biofuel projects, including open-ocean cultivation systems, with grants from USD 2 million to over USD 7 million.
- UK and EU - UKRI and Horizon 2020 focus on biofuel production scalability and commercialization from macroalgae. The UK's BBSRC is also a primary funder.
- Australia and New Zealand - The Australian CRC and New Zealand's Ministry of Business fund bioproduct development and integration with traditional agriculture.[xxxv]

Private investment from energy conglomerate Innoenergy went to Nordic Seafarm to enhance seaweed production with the eventual aim of biofuel production.[xxxvi] GOA Ventures, a spin-off of the Dutch chemical multinational DSM-Firmenich, has attracted funding from the Dutch energy sector to advance its biogas technology derived from seaweed.

3.3.5. Barriers to Market Entry

i. Regulatory Barriers (G)

Due to varying governmental policies, national energy demands are politically driven and challenging to predict. Over 80 countries support bioenergy through subsidies, recognizing its crucial role in achieving net-zero emissions by increasing modern bioenergy use and phasing out traditional biomass. This focus on advanced biomass sources like seaweed-based energy reflects a strategic shift, making market forecasts difficult due to political influences.

In **Southeast Asia**, countries such as **Indonesia**, **Malaysia**, and **Thailand** implement biofuel blending mandates to reduce dependence on imported fossil fuels. Indonesia's B35 mandate is among the most ambitious globally. However, at the same time, the Southeast Asian market is considered to present unique regulatory and logistical challenges. Large state-owned companies are cautious of adopting alternative technologies, as fossil fuels dominate energy production in the region. Efforts to engage with these monopolies reveal a tendency to prioritize conventional, well-established energy sources, underscoring the need for strong policy incentives and government-backed initiatives to advance bioenergy. While promising policy frameworks are under development, like those driven by the ASEAN Green Initiative, they have yet to translate into tangible support for novel biofuel solutions at the required scale. Challenges include fragmented regulations without a unified framework and ensuring sustainable feedstock production to prevent environmental harm. **India** introduced the National Policy on Biofuels to reduce energy imports, encouraging biofuel production from non-food feedstocks and increasing ethanol content in gasoline to lower emissions and boost domestic production.[xxxvii] [xxxviii]

In **Latin America**, **Brazil** pioneered biofuel regulations with ethanol blending since 1976. Its biodiesel program reduces diesel use, promotes social inclusion, and supports diverse biodiesel sources. The RenovaBio program incentivizes low-carbon biofuel production, enhancing energy security and mitigating greenhouse gas emissions.[xxxix] **Argentina** supports ethanol and biodiesel blending, focusing on energy diversification and aligning with global greenhouse gas reduction efforts. Regulatory harmonization within Mercosur promotes regional energy security and market access.

In the **Caribbean**, nations like **Belize** are converting municipal waste and sargassum into diesel replacements, enhancing local energy production and waste management. Countries like **Jamaica** and the **Dominican Republic** have bioethanol blending mandates and waste-to-energy initiatives to reduce fossil fuel reliance and meet climate targets. Regional collaboration through the Caribbean Sustainable Energy Roadmap and Strategy (C-SERMS) supports energy resilience via renewables.[xl]

Given the fragmented nature of the Caribbean market due to its geography and diverse nations, establishing a regional association for seaweed could align activities. Such an organization would aggregate stakeholders with common interests in advancing seaweed-based biofuel, thereby reducing redundant efforts undertaken at individual company levels or local governments. This collaborative approach would streamline initiatives to address regulatory challenges while pooling resources—financial, human, and knowledge-based—to maximize regional opportunities. A regional association could accelerate progress in tackling shared challenges and enhancing market potential by fostering cooperation among various entities, including agencies and local governments.

ii. Customer Acceptance

Customer acceptance and investor confidence remain a significant hurdle for the seaweed fuel industry. Stakeholders express concerns regarding the reliability of seaweed farming technology and its maturity level , which isnecessary for large-scale investments. Particularly in high-energy-demand sectors like aviation, there is skepticism about seaweed-derived fuels competing with conventional fuels on reliability and cost-effectiveness. To become viable options, seaweed-based fuels must demonstrate cost-competitive production capabilities alongside scalable operations that consistently convert biomass into crude oil alternatives and essential platform chemicals.

Limited awareness of seaweed fuels further exacerbates these challenges. Unlike other renewable energy sources such as solar or wind power, seaweed fuels lack visibility in mainstream discussions about renewable energy solutions. Industry insiders emphasize the importance of outreach to policymakers and potential investors to build credibility and showcase the benefits of seaweed biofuels. This is particularly vital in the aviation sector, where partnerships could validate the practical application of seaweed fuels and encourage wider adoption.

iii. Cost Competitiveness / Competition

Biofuel production from cultivated seaweed may never become economically feasible, even at a larger scale and reduced cost. The primary reason we do not see seaweed-based bioenergy products on the market today is that current production systems are not economically viable[xli]. The conventional forms of seaweed biomass supply are currently not at scale or simply too expensive to turn into bioenergy, which is low cost compared to other products and applications. Harvesting the excess Sargassum in the Caribbean may present a unique opportunity. Experts say that it can be economically viable to collect and process this seaweed into biomethane or biofuel that could be cost-competitive with today's fossil-based products. Turning the Sargassum from a burden into an asset, with co-benefits being the improved ecological, societal ,and economic effects of this unique algae bloom on local communities.[xlii]

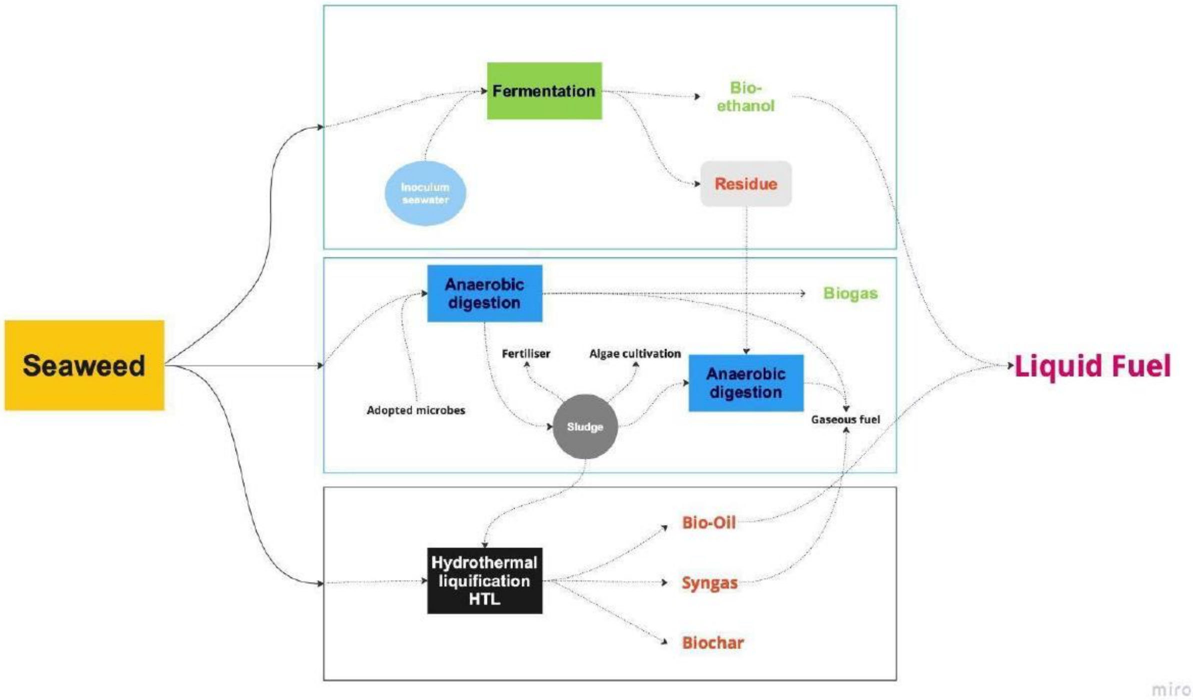
According to our research, the economic feasibility of seaweed-based fuels relies on achieving a feedstock cost under $100 per ton. This target aligns seaweed with agricultural waste biomass, priced around $100 per ton, making it competitive with other biofuel feedstocks. However, meeting this benchmark would require substantial advancements in labor productivity, large-scale marine engineering, and crop science innovations. Achieving these reductions is costly, especially considering the capital-intensive nature of commercial-scale digesters for converting seaweed biomass into bioenergy. For instance, a digester designed to support regional energy demands could cost upwards of $1.5 million, with larger facilities incurring even greater costs. Nonetheless, there is optimism that seaweed digesters could become a cost-effective alternative to diesel generators in high-cost energy regions like isolated islands. At larger scales, such systems could also qualify for competitive feed-in tariffs in regions with favorable energy policies, providing a pathway toward more economical biofuel production.

3.3.6. Technology Status

Various methods for converting seaweed into bioenergy have been developed; however, technical and engineering difficulties remain prevalent. The extraction process begins with determining whether an initial drying step is necessary before proceeding with energy extraction methods such as direct combustion or anaerobic digestion (AD). Given that seaweed contains 80-90% water content, wet biomass without drying is often more efficient than drying methods that consume additional resources[xliii]. In addition, energy content on a dry basis is relatively lower for some of the tested species, which could result in high costs of recovering, transporting, and handling biomass.

Anaerobic digestion is currently a technologically advanced method for converting seaweed into biogas (approximately 60% methane). This biogas can be utilized for used to generate electricity and generation into transportation fuel.

Figure 7: *Different routes to biofuel production from seaweed for enhanced energy recovery and zero-waste approach. Illustration adapted from Faisal et al. 2022*[xliv]



The technology readiness level (TRL) for various seaweed-based fuel production processes varies significantly. In contrast, ethanol fermentation and hydrothermal conversion technologies exist at medium TRL levels, anaerobic digestion has reached a high TRL due to its established infrastructure and environmental benefits. An example from the Caribbean is Rum & Sargassum Inc – a Barbados-based company that produces renewable compressed natural gas using low-cost locally sourced organic inputs, including rum industry wastewater, Sargassum seaweed, and Barbados Blackbelly sheep manure.

The table below summarizes possible techniques applied, the advantages and disadvantages of each approach, and the technology readiness level (TRL).

Comparison of most common technologies and bioenergy products from seaweed:

Technology	Product	Advantages	Disadvantages	TRL
Anaerobic Digestion (AD)	Methane	• Suitable for wet biomass • High energy conversion • Versatile output (gas/ hydrogen) • Mature technology • Existing infrastructure • Considered environmentally friendly • Potential for co-digestion with other feedstocks	• Salts in seaweed require pre-treatment • The effect of seasonal variety of biomass is unknown • High ash content in seaweeds might affect long-term digestion • Inhibitors (ammonia, sulfide, metals and polyphenols) • Safety and storage	**HIGH**
Hydrothermal Conversion or Liquefaction (HTC or HTL)	Bio-Crude oil or HTL liquid	• Suitable for wet biomass • Utilize the entire organic fraction of the feedstock • Versatile high energy dense liquid output	• Bio-crude may need to be further upgraded to obtain fuel with good performance	**MEDIUM**
Ethanol Fermentation	Bio-Ethanol	• Environmentally friendly technology • It can be blended with petrol • High demand from the chemical industry and SAFs	• Drying may be necessary • Low energy yield, while the process is energy-intensive	**MEDIUM**

		• Existing infrastructure		
Dark Fermentation or Photofermentation	Hydrogen	• Suitable for wet biomass • The high energy value of Hydrogen • No carbon emission on combustion • It can be blended with methane	• Low energy yield, while the process is energy-intensive • Salts adversely affect the gas yield • Need for high compression to transport and store • Safety issues due to high compression	**LOW**
Anaerobic Digestion + Microbial Fermentation	Bio-Diesel	• It can be blended with conventional diesel without engine modification	• The process is not fully understood and only tested at lab scale	**LOW**
Acetone-Butanol-Ethanol Fermentation	Bio-Butanol	• Highly advanced fuel • It can be blended in with conventional petrol	• Immature technology • Very low yields • Not recognized as biofuel	**LOW**

iv. Technology Bottlenecks

The composition of seaweeds varies significantly across species, influencing their potential for biofuel production. Red seaweeds exhibit a carbohydrate content of 55-65%, making them more favorable for bioethanol production than other seaweed types. In contrast, brown seaweeds contain alginate, mannitol, glucan, and laminarin, which commonly used industrial microbes may not efficiently metabolize during fermentation. This limitation often necessitates the use of specific enzymes, thereby increasing production costs. Comprehensive compositional analysis, including seasonal variations, is essential for selecting appropriate processing methods tailored to specific biomass or species. Furthermore, composition-specific pre-treatment and carbohydrate hydrolysis techniques are needed.

Many bioprocessing technologies have only been tested at a lab scale, leading to new challenges when scaled up. To give a few examples, hydrothermal liquefaction (HTL) demand high energy inputs, reducing energy returns. Effective pre-treatment to extract sugars remains costly and may produce by-products that hinder fermentation.[xlv] Freshwater reliance raises concerns due to global scarcity, prompting research into seawater alternatives. Energy-intensive drying processes increase the cost of converting wet biomass.

v. R&D Needs

Various biofuel production pathways exhibit differing technology readiness levels, potential yields, co-products, and infrastructure requirements, highlighting the necessity for further research to optimize the use of seaweeds in biofuel applications. Improvements in processing technologies to optimize energy output from raw biomass will be necessary to make seaweed biofuels economically sustainable at larger scales. Incorporating biorefineries into the seaweed value chain can enhance economic viability by enabling cascading biomass utilization. Biorefineries are capable of transforming seaweed into various products—such as biofuels, bioplastics, animal feed, and fertilizers—thereby maximizing resource efficiency and generating multiple revenue streams.[xlvi]

Developing higher-yield seaweed strains suited for biofuels is critical, as most strains are food-oriented. Research into tropical seaweeds shows potential but demands extensive R&D for commercial viability. Variability in seaweed composition complicates biofuel efficiency, requiring constant parameter adjustments. Inhibitory compounds found in seaweeds can hinder microbial processes, reducing biogas yield. In addition, innovation in farming methods that boost yield per hectare and lower operational costs of cultivation and processing are vital.

vi. Scalability

Without the appropriate infrastructure to enable mass cultivation, the biofuel sector faces difficulties fulfilling the substantial biomass demands essential for commercial sustainability. Industry pilot projects with major energy corporations have shown that at least hundreds of thousands of tons of seaweed are needed yearly to generate the required energy volumes, highlighting the crucial need for a consistent feedstock supply. These trials highlight the logistical obstacles in achieving the necessary production scale, underscoring the importance of efficient, large-scale supply chains and durable, high-output farming systems.

Proponents suggest it is only a question of timing until offshore cultivation technologies allow for the scale to supply low-cost seaweed biomass that makes energy production economically feasible. The U.S. Department of Energy Advanced Research Project Agency-e's

(ARPA-e's) MARINER program has worked on creating prototypes for scalable farmed systems that can be deployed in deeper waters to grow biomass stocks for biofuels. The MARINER production cost goal was roughly equivalent to ~$75 USD per metric ton dry weight. According to program participants, the production of seaweed-derived biofuel will not be economically profitable for at least ten years.[xlvii]

vii. Infrastructure needs

Seaweed-derived energy alternatives, like biomethane and biofuel, could integrate into existing energy infrastructures, offering a practical solution for diverse energy distribution systems. Energy distribution infrastructure varies from country to country. This means that different forms of biobased energy will be required according to existing energy grid infrastructure. Due to its similar characteristics to fossil-based energy products seaweed, derived alternatives, especially biomethane, can easily be carried through the existing grid and pipelines without any additional infrastructure investment requirements. The same goes for seaweed-derived crude oil that can be further derived from existing refinery infrastructure.

Seaweed bioenergy production will likely remain coastal, primarily in regions with high energy costs. It's reasonable to conclude that even at a commercial level, bioenergy sourced from seaweed will predominantly be localized along coastlines. Refineries and other energy processing facilities, such as anaerobic digesters, must be near the coast where seaweed is readily available. Transporting seaweed over long distances would be economically impractical and require methods to stabilize the wet biomass for extended shelf life. Developing seaweed-to-energy infrastructure may only appeal to areas without renewable energy sources like wind and solar. This could be due to unfavorable climatic conditions for these alternatives or the increasing occurrence of

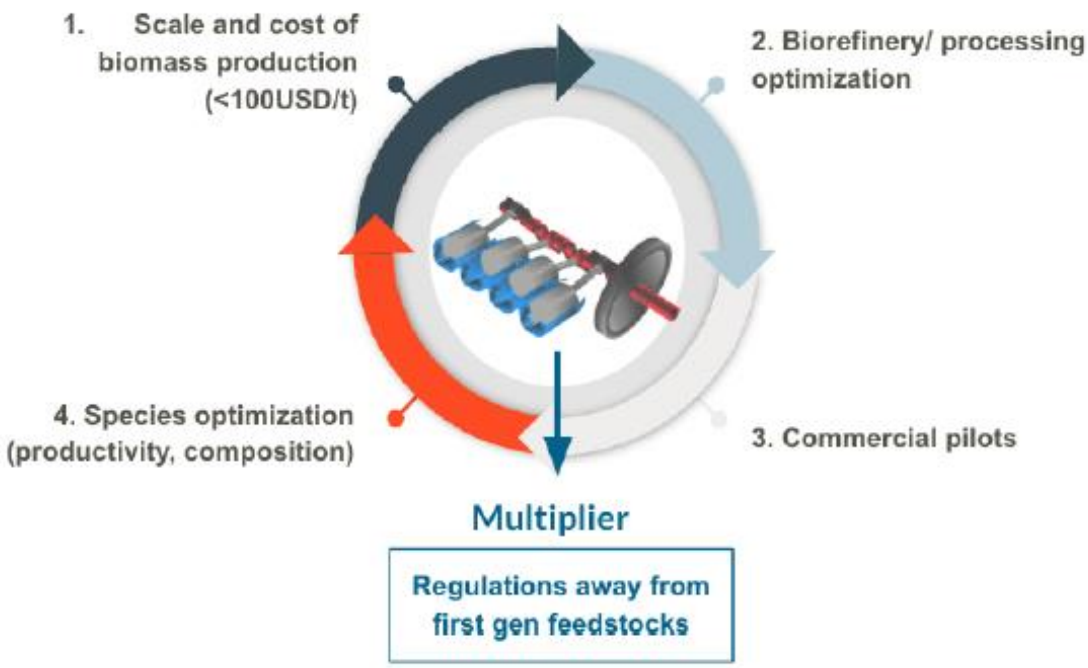
natural disasters that threaten turbines and solar installations, such as some of the Caribbean islands or parts of Southeast Asia that receive typhoons.[xlviii] [xlix]

3.4. Investment opportunities

3.4.1. Overview of key investment area

While technically feasible, the current scenario of seaweed cultivation cannot achieve the scale, production efficiency, and production costs required for supporting a seaweed-based biofuels sector in near to mid-term. The infrastructure needs of seaweed bioenergy present key investment opportunities through focused trials that demonstrate scalability and cost-efficiency.

Figure 8: What could enhance the value chain for scaling bioenergy sourced from cultivated seaweed and algal blooms?



1. A viable seaweed-based bioenergy sector, first and foremost, **requires a large-scale biomass supply at a much lower production cost than what is available today**. Addressing the biomass needed for bioenergy requires moving beyond traditional shallow-water farming. Automation with drones and robotic harvesters can lower labor dependence and improve scalability. Large-scale marine operations, like automated offshore platforms and high-capacity conveyors, are crucial investment areas that enhance continuous seaweed processing.
2. **Developing integrated processing facilities for products beyond biofuels.** Nearer-term opportunities exist to use seaweed in an integrated biorefinery context to make higher-value food, feed, nutraceutical, and oleochemical bio-products, which can help drive the economic development for bioenergy production.
3. **Investing in commercial pilots** is another area of high impact. Constructing commercial pilot-scale bio-digesters for testing will assess scalability, operational efficiency, and economics. Supporting these projects can showcase bio-digesters capacity to provide cost-effective renewable energy, easing regulatory hurdles and facilitating market entry.
4. **Further R&D investments in resilient, high-yield seaweed strains with optimized composition for biofuel** production can further reduce the production cost for seaweed biomass. By financing research centers focusing on strain development, investors can secure valuable IP and licensing as demand for biofuel feedstock grows with considerations of genetically enhanced strains that optimize yield in varying marine settings. However, this is a long-term opportunity.

Regulatory support is a critical multiplier for accelerating the growth of the seaweed bioenergy sector. Moving away from first-generation feedstocks through supportive regulations can create a unique opportunity for investment in seaweed biofuels. Identifying regions with favorable regulatory conditions, high energy costs, and supportive renewable energy policies can significantly de-risk investments in this sector. Governments can stimulate innovation and investment while aligning with climate goals by promoting regulations that favor third-generation feedstocks like seaweed. Tax incentives or subsidies may be required to offset the biofuel production costs partially. Supporting market assessments to pinpoint regions where seaweed biofuel can gain traction—especially where renewable energy policies are supportive—can de-risk investments.

4. High-level Market Insights - Seaweed-based Animal Feed Additives

Feed additives is a growing segment within the global animal feed market and looking towards natural health supplements. The global animal feed market, valued at approximately $482 billion, includes a $40 billion segment for feed additives, which is growing at a CAGR of around 4%.[l] This expansion reflects a broader industry shift toward sustainable and natural alternatives, driven by rising environmental concerns, increasing demand for natural feed ingredients, and the need to replace synthetic additives like zinc. Several seaweed species have shown potential to enhance animal health, particularly gut health if applied as a feed additive and functional ingredient. A healthier gut microbiome is believed to improve immunity, enhance mineral absorption, and increase iron uptake, boosting oxygen transport in the blood. However, there are only a few products and further R&D and validation are required on animal safety, health, and productivity gains for different seaweed species and derived products. Supply chain limitations significantly constrain scalability in the farmed seaweed industry for commercial feed additives. Additionally, scale speed is hindered by the lengthy, costly testing and validation process required to gain buyer acceptance.

5. Recommendations for Investment Areas to Catalyze Seaweed-Based Animal Feed Additives in the Global South

1. Supply Chain Development

Develop partnerships with local seaweed farmers and processors to create a reliable supply chain for high-quality raw materials. This will help mitigate supply chain limitations and ensure consistent product quality. Implement robust quality assurance processes to monitor the consistency of raw materials sourced from local suppliers, ensuring that the seaweed used in feed additives meets high standards for efficacy and safety. Form off-take agreements with local livestock producers to secure commitments for purchasing seaweed-based feed additives. This can provide a stable revenue stream while encouraging producers to adopt innovative feed solutions.

2. Product Development and comprehensive R&D Trials

Focus on customizing seaweed-based feed additives to meet specific livestock live stage needs and health challenges. This targeted approach will enhance product relevance and increase adoption among farmers. Invest in extensive research and development trials to evaluate the efficacy and safety of seaweed-based feed additives across diverse livestock species and production systems. These trials should focus on optimizing formulations tailored to specific regional conditions and livestock health challenges. By systematically assessing performance metrics such as growth rates, feed conversion efficiency, and overall animal health, stakeholders can build a robust evidence base that supports adopting these innovative solutions.

3. Regulatory Navigation and Advocacy

Collaborate with industry associations to advocate for clearer and more streamlined regulations regarding seaweed-based feed additives. This can lower barriers to entry and encourage wider adoption in the agricultural sector. Establish dedicated teams to navigate complex regulatory frameworks governing feed additives. This will involve engaging with regulatory bodies early in the product development process to facilitate smoother approvals and reduce time-to-market.

4. Market Demand Enhancement and Consumer Engagement

Sharing findings from successful trials with farmers and industry stakeholders will enhance credibility and encourage wider acceptance of seaweed-based products. Work closely with local agricultural organizations, NGOs, and government agencies to promote the benefits of seaweed-based feed additives, fostering a collaborative environment that supports sustainable agricultural practices. Targeted educational campaigns can raise awareness about the benefits of seaweed in animal nutrition, emphasizing its role in improving livestock health and sustainability and capitalizing on the increasing awareness of sustainable agricultural practices.

6. High-level Market Insights - Seaweed-based Bioplastics

Plastics represent a large and ever-growing global market; however, concern over plastic's impact has increased interest in more sustainable practices. Bioplastics make up a small but growing portion of the plastics market. While still a niche sector within the broader bioplastics industry, seaweed-based bioplastics have made notable technological advancements, integrating conventional and modern methods to convert seaweed into functional biomaterials. These materials are primarily cellulose and PLA-based, derived from various seaweed species that contribute unique polysaccharides, with brown, red, and green seaweeds, offering specific properties valuable for bioplastic production.[li] The seaweed-based bioplastics products in the pipeline are primarily designed to fit applications in the flexible and single-use packaging sector. However, most seaweed-based biomaterials available today are around 8-10 times higher priced than traditional plastics and around 2-10 times higher than other bioplastics, with feedstock being a substantial cost factor. While some startups have successfully scaled production methods to pilot levels, large-scale production of seaweed-based bioplastics remains a significant challenge. To achieve scale and profitability, bioplastics companies need hundreds of thousands, and preferably hundreds of millions of tonnes of seaweed - currently unavailable volumes.

7. Recommendations for Investment Areas to Catalyze Seaweed-Based Biopackaging in the Global South

1. R&D and Pilot Projects

To improve product and cost-effectiveness, R&D must be funded to tailor seaweed-based materials to regional market and supply chain contexts. Biodegradability trials across various regulatory environments will also be necessary to demonstrate compliance with local waste management standards. These trials ensure that seaweed-based packaging aligns with local disposal processes and addresses practical use in diverse regions.

2. Infrastructure Investments

Investing in regional seaweed supply chains can reduce transportation costs and lower the environmental impact associated with long-distance sourcing. Developing regional extraction and processing facilities can improve cost efficiency and streamline the sourcing of seaweed materials. Additionally, major partnerships with manufacturers will support the necessary expansion of production lines for novel materials, facilitating the broader adoption of packaging alternatives.

3. Market Development and Consumer Engagement

Educational campaigns focused on the environmental benefits of biodegradable, seaweed-based packaging can build awareness among consumers and industry stakeholders. Partnering with prominent regional brands, such as those in the food service or retail sectors, can increase visibility and encourage consumer adoption of sustainable packaging options.

4. Regulatory Navigation and Advocacy

Supporting legal and compliance teams to navigate regulatory landscapes can facilitate smoother market entry, particularly in regions where sustainable packaging standards are still developing. Sharing case studies from more regulated markets, such as Europe, may also encourage shifts toward eco-friendly policies in less regulated regions by demonstrating the feasibility and benefits of seaweed-based packaging.

References

ASEAN Centre for Energy. "Fuelling National and Regional Ambitions with Shared Biofuel Strength within ASEAN Countries." *ASEAN Centre for Energy* (blog). Accessed November 5, 2024. https://aseanenergy.org/post/fuelling-national-and-regional-ambitions-with-shared-biofuel-strength-within-asean-countries/

Baghel, Ravi S. "Developments in Seaweed Biorefinery Research: A Comprehensive Review." *Chemical Engineering Journal* 454 (February 15, 2023): 140177. https://doi.org/10.1016/j.cej.2022.140177.

Biofuels International. "Southeast Asia Primed to Play Key Role in SAF Growth, Says Boeing | Biofuels International Magazine," September 3, 2024. https://biofuels-news.com/news/southeast-asia-primed-to-play-key-role-in-saf-growth-says-boeing/.

Biostimulant.com. "REGULATORY." Accessed December 17, 2024. https://www.biostimulant.com/regulatory/.

BloombergNEF. "2022 Sustainable Aviation Fuel Outlook." *BloombergNEF* (blog), August 31, 2022. https://about.bnef.com/blog/2022-sustainable-aviation-fuel-outlook/.

Boukhari, Mohammed EL Mehdi EL, Mustapha Barakate, Youness Bouhia, and Karim Lyamlouli. "Trends in Seaweed Extract Based Biostimulants: Manufacturing Process and Beneficial Effect on Soil-Plant Systems." *Plants* 9, no. 3 (March 12, 2020): 359. https://doi.org/10.3390/plants9030359.

ClimaCrew. "ClimaCrew Launch of Climazyme K+ for Biostimulants," 2023. https://www.linkedin.com/posts/climacrew_marine-kappaphycus-maharashtra-activity-7097527896113623042-a0KG.

Commodity Insights Live. "Fuels of the Future: Unpacking the Pathway for Advanced Fuels in Brazil." Commodity Insights Live, May 10, 2024. https://cilive.com/commodities/agriculture/news-and-insight/051024-fuels-future-brazil.

Daily Express. "Sabah to Gain from Bio-Based Initiatives | Daily Express Malaysia - Sabah's Leading News Portal." Accessed November 8, 2024. https://www.dailyexpress.com.my/news/216788/sabah-to-gain-from-bio-based-initiatives/.

Deepika, Charu, Gokare A. Ravishankar, and Ambati Ranga Rao. "Potential Products from Macroalgae: An Overview." In *Sustainable Global Resources Of Seaweeds Volume 1: Bioresources , Cultivation, Trade and Multifarious Applications*, edited by Ambati Ranga Rao and Gokare A. Ravishankar, 17–44. Cham: Springer International Publishing, 2022. https://doi.org/10.1007/978-3-030-91955-9_2.

Duarte, Carlos, Jiaping Wu, Xi Xiao, Annette Bruhn, and Dorte Krause-Jensen. "Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation?" *Frontiers in Marine Science* 4 (April 12, 2017). https://doi.org/10.3389/fmars.2017.00100.

EIT InnoEnergy. "EIT InnoEnergy and Inter IKEA Group Invest in Nordic SeaFarm," November 4, 2024. https://www.innoenergy.com/news-events/eit-innoenergy-and-inter-ikea-group-invest-in-nordic-seafarm/.

Emma M Brown, Philip J Allsopp, Pamela J Magee, Chris IR Gill. "Seaweed and Human Health | Nutrition Reviews | Oxford Academic," 2014. https://academic.oup.com/nutritionreviews/article/72/3/205/1853561?login=false.

Ertani, Andrea, Ornella Francioso, Anna Tinti, Michela Schiavon, Diego Pizzeghello, and Serenella Nardi. "Evaluation of Seaweed Extracts From Laminaria and Ascophyllum Nodosum Spp. as Biostimulants in Zea Mays L. Using a Combination of Chemical, Biochemical and Morphological Approaches." *Frontiers in Plant Science* 9 (April 6, 2018). https://doi.org/10.3389/fpls.2018.00428.

Faisal, Shah, Abdelrahman Zaky, Qingyuan Wang, Jin Huang, and Abdelfatah Abomohra.

"Integrated Marine Biogas: A Promising Approach towards Sustainability." *Fermentation* 8, no. 10 (October 2022): 520. https://doi.org/10.3390/fermentation8100520.

FAO. *The State of World Fisheries and Aquaculture 2022: Towards Blue Transformation*. The State of World Fisheries and Aquaculture (SOFIA) 2022. Rome, Italy: FAO, 2022. https://doi.org/10.4060/cc0461en.

Hatch Innovation Services. "Global Seaweed New and Emerging Markets Report 2023." World Bank, 2023. https://www.worldbank.org/en/topic/environment/publication/global-seaweed-new-and-emerging-markets-report-2023.

———. "Seaweed Insights." Seaweed Insights, 2022. https://seaweedinsights.com/.

———. "Viability Analysis for an International Tropical Seaweed Resilience Institute," 2024.

Hermans, Steven. "Phyconomy 2024, Newsletter." 2024.

Hurtado, Anicia Q., Iain C. Neish, and Alan T. Critchley. "Phyconomy: The Extensive Cultivation of Seaweeds, Their Sustainability and Economic Value, with Particular Reference to Important Lessons to Be Learned and Transferred from the Practice of Eucheumatoid Farming." *Phycologia* 58, no. 5 (September 3, 2019): 472–83. https://doi.org/10.1080/00318884.2019.1625632.

International Energy Agency. "Biofuels – Energy System." IEA, 2024. https://www.iea.org/energy-system/low-emission-fuels/biofuels.

———. "Carbon Accounting for Sustainable Biofuels – Analysis." IEA, July 23, 2024. https://www.iea.org/reports/carbon-accounting-for-sustainable-biofuels.

International Renewable Energy Agency. "Sustainable Bioenergy Potential in Caribbean Small Island Developing States," February 2024.

Jardin, Patrick du. "Plant Biostimulants: Definition, Concept, Main Categories and Regulation." *Scientia Horticulturae*, Biostimulants in Horticulture, 196 (November 30, 2015): 3–14. https://doi.org/10.1016/j.scienta.2015.09.021.

Kanters, Janet. "Dominican Republic Launches First Blue Biotechnology Company." *New AG International* (blog), September 26, 2024. http://www.newaginternational.com/biostimulants/dominican-republic-launches-first-blue-biotechnol ogy-company/.

———. "Futureco Bioscience Expands Commercial Operations in Mexico." *New AG International* (blog), November 8, 2023. http://www.newaginternational.com/biostimulants/futureco-bioscience-expands-commercial-operatio ns-in-mexico/.

———. "Futureco Bioscience Opens Subsidiary in Costa Rica." *New AG International* (blog), February 20, 2024. http://www.newaginternational.com/biostimulants/futureco-bioscience-opens-subsidiary-in-costa-rica/.

Katsaris, Michele. "South American Seaweed Extract Biostimulants Market Growing Fast." *AgriBusiness Global* (blog), February 14, 2024. https://www.agribusinessglobal.com/plant-health/biostimulants/south-american-seaweed-extract-bio stimulants-market-growing-fast/.

Kostas, Emily T., Jessica M. M. Adams, Héctor A. Ruiz, Gabriela Durán-Jiménez, and Gary J. Lye. "Macroalgal Biorefinery Concepts for the Circular Bioeconomy: A Review on Biotechnological Developments and Future Perspectives." *Renewable and Sustainable Energy Reviews* 151 (November 1, 2021): 111553. https://doi.org/10.1016/j.rser.2021.111553.

Lim, C., S. Yusoff, C. G. Ng, P. E. Lim, and Y. C. Ching. "Bioplastic Made from Seaweed Polysaccharides with Green Production Methods." *Journal of Environmental Chemical Engineering* 9, no. 5 (October 1, 2021): 105895. https://doi.org/10.1016/j.jece.2021.105895.

Mahapatra, Sangita, Dilip Kumar, Brajesh Singh, and Pravin Kumar Sachan. "Biofuels and Their Sources of Production: A Review on Cleaner Sustainable Alternative against Conventional Fuel, in the Framework of the Food and Energy Nexus." *Energy Nexus* 4 (December 30, 2021): 100036. https://doi.org/10.1016/j.nexus.2021.100036.

Mukherjee, A., and J. S. Patel. "Seaweed Extract: Biostimulator of Plant Defense and Plant

Productivity." *International Journal of Environmental Science and Technology* 17, no. 1 (January 1, 2020): 553–58. https://doi.org/10.1007/s13762-019-02442-z.

Mulyati, Heti, and Jutta Geldermann. "Managing Risks in the Indonesian Seaweed Supply Chain." *Clean Technologies and Environmental Policy* 19, no. 1 (January 1, 2017): 175–89. https://doi.org/10.1007/s10098-016-12197.

Nabti, E., B. Jha, and A. Hartmann. "Impact of Seaweeds on Agricultural Crop Production as Biofertilizer." *International Journal of Environmental Science and Technology* 14, no. 5 (May 1, 2017): 1119–34. https://doi.org/10.1007/s13762-016-1202-1.

Ocean Harvest Technology. "Company-Presentation," 2024. https://oceanharvesttechnology.com/wp-content/uploads/Ocean-Harvest-Technology-Company-Presentation.pdf.

Pandey, Samyak. "Asian Countries Agree to Establish Sustainable Fuel Supply Chain with a Focus on Biofuels," August 21, 2024. https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/agriculture/082124-asi an-countries-agree-to-establish-sustainable-fuel-supply-chain-with-a-focus-on-biofuels.

Pantoja, Alvaro. "Los Impulsores Del Crecimiento Del Mercado de Bioestimulantes En América Latina." Biologicals Latam, April 19, 2023. https://biologicalslatam.com/en/los-impulsores-del-crecimiento-del-mercado-de-bioestimulantes-en-a merica-latina/.

Piyatida (Tung) Pukclai, Ph.D. "Biocontrol Legislation in Some Selected Asia Countries. 3: Regulatory Environment." ABIM 2023, Annual Biocontrol Industry Meeting, October 24, 2023.

Pukclai, Piyatida. "Emerging Markets for Biostimulants." *AgriBusiness Global* (blog). Accessed November 5, 2024. https://www.agribusinessglobal.com/special-sections/emerging-markets-for-biostimulants/.

———. "SE Asia's Local Restrictions Increase Gap in Product Availability." *AgriBusiness Global* (blog). Accessed November 5, 2024. https://www.agribusinessglobal.com/special-sections/regulations/.

Robledo, Daniel, Erika Vázquez-Delfín, Yolanda Freile-Pelegrín, Román Manuel Vásquez-Elizondo, Zujaila Nohemy Qui-Minet, and Adán Salazar-Garibay. "Challenges and Opportunities in Relation to Sargassum Events Along the Caribbean Sea." *Frontiers in Marine Science* 8 (July 22, 2021). https://doi.org/10.3389/fmars.2021.699664.

Salehi, Bahare, Javad Sharifi-Rad, Ana M. L. Seca, Diana C. G. A. Pinto, Izabela Michalak, Antonio Trincone, Abhay Prakash Mishra, Manisha Nigam, Wissam Zam, and Natália Martins. "Current Trends on Seaweeds: Looking at Chemical Composition, Phytopharmacology, and Cosmetic Applications." *Molecules* 24, no. 22 (January 2019): 4182. https://doi.org/10.3390/molecules24224182.

Samoraj, Mateusz, Derya Çalış, Krzysztof Trzaska, Małgorzata Mironiuk, and Katarzyna Chojnacka. "Advancements in Algal Biorefineries for Sustainable Agriculture: Biofuels, High-Value Products, and Environmental Solutions." *Biocatalysis and Agricultural Biotechnology* 58 (June 1, 2024): 103224. https://doi.org/10.1016/j.bcab.2024.103224.

"Senate Approves Regulatory Framework for Bioinputs in Brazil: A Milestone for Agricultural Sustainability - DANIEL LAW." Accessed December 17, 2024. https://www.daniel-ip.com/en/client-alert/senate-approves-regulatory-framework-for-bioinputs-in-bra zil-a-milestone-for-agricultural-sustainability/.

Soares Dias, Ana Paula, Bruna Rijo, Francisco Santos, Rui Galhano dos Santos, and Tânia Frade. "Overview on Biofuels Production in a Seaweed Biorefinery." *Science of The Total Environment* 884 (August 1, 2023): 163714. https://doi.org/10.1016/j.scitotenv.2023.163714.

Soleymani, Mohsen, and Kurt A. Rosentrater. "Techno-Economic Analysis of Biofuel Production from Macroalgae (Seaweed)." *Bioengineering* 4, no. 4 (December 2017): 92. https://doi.org/10.3390/bioengineering4040092.

Spillias, Scott, Rachel Kelly, Richard S. Cottrell, Katherine R. O'Brien, Ran-Young Im, Ji Yoon Kim, Chuan Lei, et al. "The Empirical Evidence for the Social-Ecological Impacts of Seaweed Farming." *PLOS Sustainability and Transformation* 2, no. 2 (February 1, 2023): e0000042. https://doi.org/10.1371/journal.pstr.0000042.

Sujeeth, Neerakkal, Veselin Petrov, Kieran J. Guinan, Fiaz Rasul, John T. O'Sullivan, and Tsanko S. Gechev. "Current Insights into the Molecular Mode of Action of Seaweed-Based Biostimulants and the Sustainability of Seaweeds as Raw Material Resources." *International Journal of Molecular Sciences* 23, no. 14 (January 2022): 7654. https://doi.org/10.3390/ijms23147654.

The Nature Conservancy 2023. "Analysis of Farmed Seaweed Carbon Crediting and Novel Markets to Help Decarbonize Supply Chains." The Nature Conservancy, 2023.

Torres, M. D., Stefan Kraan, and Herminia Domínguez. "Seaweed Biorefinery." *Reviews in Environmental Science and Bio/Technology* 18, no. 2 (June 1, 2019): 335–88. https://doi.org/10.1007/s11157-019-09496-y.

United Nations Environment Programme. "Sargassum White Paper - Sargassum Outbreak in the Caribbean: Challenges, Opportunities and Regional Situation. Panama: UNEP.," 2018. https://www.unep.org/cep/resources/publication/sargassum-white-paper-turning-crisis-opportunity.

Valderrama, Diego, Junning Cai, Nathanaël Hishamunda, Neil B. Ridler, and Food and Agriculture Organization of the United Nations, eds. *Social and Economic Dimensions of Carrageenan Seaweed Farming*. FAO Fisheries and Aquaculture Technical Paper 580. Rome: Food & Agriculture Organization of the United Nations, 2013.

Wadduwage, Jenendra, Hongwei Liu, Eleonora Egidi, Brajesh K. Singh, and Catriona A. Macdonald. "Effects of Biostimulant Application on Soil Biological and Physicochemical Properties: A Field Study." *Journal of Sustainable Agriculture and Environment* 2, no. 3 (2023): 285–300. https://doi.org/10.1002/sae2.12057.

Worldfish. "Unlocking Seaweed's Potential for Global Sustainability." WorldFish, September 4, 2024. https://worldfishcenter.org/blog/unlocking-seaweeds-potential-global-sustainability.

Xiao, Xi, Susana Agusti, Fang Lin, Ke Li, Yaoru Pan, Yan Yu, Yuhan Zheng, Jiaping Wu, and Carlos M. Duarte. "Nutrient Removal from Chinese Coastal Waters by Large-Scale Seaweed Aquaculture." *Scientific Reports* 7, no. 1 (April 21, 2017): 46613. https://doi.org/10.1038/srep46613.

Yarish, Charles, Randall Brummett, Steffen Hansen, Rasmus Bjerregaard, Diego Valderrama, Neil Sims, Ricardo Radulovich, et al. *Seaweed Aquaculture for Food Security, Income Generation and Environmental Health in Tropical Developing Countries*, 2016.

Yating Jiang. "AgroPages-The 3rd Biopesticides, Biostimulants and Novel Fertilizers Asian Summit Successfully Held in Hangzhou of China-Agricultural News," March 24, 2022. https://news.agropages.com/News/NewsDetail---42307.htm.

Yuan, Grace. "Key Players, Insight Into the Layout, Application, Regulation and Development Trend of Biologicals in Latin America." Grainews, September 2023. https://news.agropages.com/News/Detail-47602.htm.

Zhao, Yiru, Nathalie Bourgougnon, Jean-Louis Lanoisellé, and Thomas Lendormi. "Biofuel Production from Seaweeds: A Comprehensive Review." *Energies* 15, no. 24 (January 2022): 9395. https://doi.org/10.3390/en15249395.

About the Subnational Climate Fund

The Subnational Climate Fund (SCF) is a global blended finance initiative that aims to invest in and scale mid-sized (5 – 75 M $USD) subnational infrastructure projects in the fields of sustainable energy, waste and sanitation, regenerative agriculture and nature-based solutions in developing countries.

The SCF finances projects with a blend of concessional and conventional capital, along with Technical Assistance grants that help mitigate risk and ensure financial and environmental goals are achieved.

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Endnotes

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[i] Yarish et al., *Seaweed Aquaculture for Food Security, Income Generation and Environmental Health in Tropical Developing Countries*; Duarte et al., "Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation?"; Xiao et al., "Nutrient Removal from Chinese Coastal Waters by Large-Scale Seaweed Aquaculture"; Emma M Brown, Philip J Allsopp, Pamela J Magee, Chris IR Gill, "Seaweed and Human Health | Nutrition Reviews | Oxford Academic"; Spillias et al., "The Empirical Evidence for the Social-Ecological Impacts of Seaweed Farming."
[ii] Baghel, "Developments in Seaweed Biorefinery Research."
[iii] Torres, Kraan, and Domínguez, "Seaweed Biorefinery."
[iv] FAO, *The State of World Fisheries and Aquaculture 2022*.
[v] Valderrama et al., *Social and Economic Dimensions of Carrageenan Seaweed Farming*.
[vi] Hurtado, Neish, and Critchley, "Phyconomy."
[vii] Hatch Innovation Services, "Viability Analysis for an International Tropical Seaweed Resilience Institute."
[viii] United Nations Environment Programme, "Sargassum White Paper - Sargassum Outbreak in the Caribbean: Challenges, Opportunities and Regional Situation. Panama: UNEP."
[ix] Robledo et al., "Challenges and Opportunities in Relation to Sargassum Events Along the Caribbean Sea."
[x] Worldfish, "Unlocking Seaweed's Potential for Global Sustainability"; Hatch Innovation Services, "Seaweed Insights."
[xi] Mulyati and Geldermann, "Managing Risks in the Indonesian Seaweed Supply Chain"; Hatch Innovation Services, "Seaweed Insights"; Kostas et al., "Macroalgal Biorefinery Concepts for the Circular Bioeconomy."
[xii] Nabti, Jha, and Hartmann, "Impact of Seaweeds on Agricultural Crop Production as Biofertilizer."
[xiii] Hatch Innovation Services, "Global Seaweed New and Emerging Markets Report 2023."
[xiv] The Nature Conservancy 2023, "Analysis of Farmed Seaweed Carbon Crediting and Novel Markets to Help Decarbonize Supply Chains."
[xv] The Nature Conservancy 2023. "Analysis of Farmed Seaweed Carbon Crediting and Novel Markets to Help Decarbonize Supply Chains."
[xvi] Sujeeth et al., "Current Insights into the Molecular Mode of Action of Seaweed-Based Biostimulants and the Sustainability of Seaweeds as Raw Material Resources"; Ertani et al., "Evaluation of Seaweed Extracts From Laminaria and Ascophyllum Nodosum Spp. as Biostimulants in Zea Mays L. Using a Combination of Chemical, Biochemical and Morphological Approaches."
[xvii] Sujeeth et al., "Current Insights into the Molecular Mode of Action of Seaweed-Based Biostimulants and the Sustainability of Seaweeds as Raw Material Resources."
[xviii] Mukherjee and Patel, "Seaweed Extract"; Salehi et al., "Current Trends on Seaweeds."
[xix] Deepika, Ravishankar, and Rao, "Potential Products from Macroalgae"; Salehi et al., "Current Trends on Seaweeds."
[xx] The Nature Conservancy 2023, "Analysis of Farmed Seaweed Carbon Crediting and Novel Markets to Help Decarbonize Supply Chains."
[xxi] Wadduwage et al., "Effects of Biostimulant Application on Soil Biological and Physicochemical Properties: A Field Study."
[xxii] Sujeeth et al., "Current Insights into the Molecular Mode of Action of Seaweed-Based Biostimulants and the Sustainability of Seaweeds as Raw Material Resources"; Ertani et al., "Evaluation of Seaweed Extracts From Laminaria and Ascophyllum Nodosum Spp. as Biostimulants in Zea Mays L. Using a Combination of Chemical, Biochemical and Morphological Approaches."
[xxiii] Mulyati and Geldermann, "Managing Risks in the Indonesian Seaweed Supply Chain."
[xxiv] Hatch Innovation Services, "Global Seaweed New and Emerging Markets Report 2023."
[xxv] Mulyati and Geldermann, "Managing Risks in the Indonesian Seaweed Supply Chain."
[xxvi] International Energy Agency, "Biofuels - Energy System."
[xxvii] Mahapatra et al., "Biofuels and Their Sources of Production."
[xxviii] International Energy Agency, "Biofuels - Energy System."
[xxix] International Energy Agency.
[xxx] International Energy Agency; International Energy Agency, "Carbon Accounting for Sustainable Biofuels – Analysis."
[xxxi] International Energy Agency, "Biofuels - Energy System."
[xxxii] BloombergNEF, "2022 Sustainable Aviation Fuel Outlook."

[xxxiii] Hatch Innovation Services, "Global Seaweed New and Emerging Markets Report 2023."
[xxxiv] Soares Dias et al., "Overview on Biofuels Production in a Seaweed Biorefinery"; Zhao et al., "Biofuel Production from Seaweeds"; Kostas et al., "Macroalgal Biorefinery Concepts for the Circular Bioeconomy."
[xxxv] Kostas et al., "Macroalgal Biorefinery Concepts for the Circular Bioeconomy."
[xxxvi] EIT InnoEnergy, "EIT InnoEnergy and Inter IKEA Group Invest in Nordic SeaFarm."
[xxxvii] Pandey, "Asian Countries Agree to Establish Sustainable Fuel Supply Chain with a Focus on Biofuels."
[xxxviii] Biofuels International, "Southeast Asia Primed to Play Key Role in SAF Growth, Says Boeing | Biofuels International Magazine"; ASEAN Centre for Energy, "Fuelling National and Regional Ambitions with Shared Biofuel Strength within ASEAN Countries."
[xxxix] Commodity Insights Live, "Fuels of the Future."
[xl] International Renewable Energy Agency, "Sustainable Bioenergy Potential in Caribbean Small Island Developing States."
[xli] Laurens and Nelson, "Chapter 21 - Sustainable Technologies for Seaweed Conversion to Biofuels and Bioproducts"; Soleymani and Rosentrater, "Techno-Economic Analysis of Biofuel Production from Macroalgae (Seaweed)."
[xlii] Tulashie et al., "The Potential Production of Biofuel from Sargassum Sp."; Orozco-González et al., "Opportunities Surrounding the Use of Sargassum Biomass as Precursor of Biogas, Bioethanol, and Biodiesel Production."
[xliii] Zhao et al., "Biofuel Production from Seaweeds."
[xliv] Faisal et al., "Integrated Marine Biogas."
[xlv] Kostas et al., "Macroalgal Biorefinery Concepts for the Circular Bioeconomy"; Soleymani and Rosentrater, "Techno-Economic Analysis of Biofuel Production from Macroalgae (Seaweed)"; Zhao et al., "Biofuel Production from Seaweeds"; Soares Dias et al., "Overview on Biofuels Production in a Seaweed Biorefinery."
[xlvi] Soares Dias et al., "Overview on Biofuels Production in a Seaweed Biorefinery."
[xlvii] Hatch Innovation Services, "Global Seaweed New and Emerging Markets Report 2023."
[xlviii] Soares Dias et al., "Overview on Biofuels Production in a Seaweed Biorefinery."
[xlix] Baghel, "Developments in Seaweed Biorefinery Research."
[l] Ocean Harvest Technology, "Company-Presentation."
[li] Lim et al., "Bioplastic Made from Seaweed Polysaccharides with Green Production Methods."