GLOBAL SEAWEED

NEW AND EMERGING MARKETS REPORT

2023

PROBLUE

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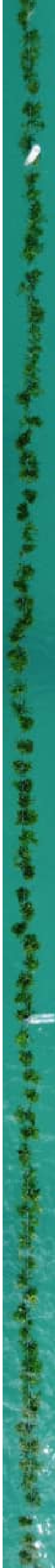

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The preparation and production of the Global Seaweed New and Emerging Markets Report was undertaken by a multidisciplinary team of World Bank Staff and consultants led by Christopher Ian Brett, Lead Agribusiness Specialist and Task Team Leader (SAGGL) and Harrison Charo Karisa (Senior Fisheries Specialist, and Co-Task Team Leader (SENGL). Valuable technical support was offered by Mekbib Haile (Senior Agriculture Economist), Vivek Prasad (AquaInvest Consultant) and Julie Mollins (Communication Specialist). This work was commissioned by the World Bank as part of the World Bank Group's AquaInvest Platform and undertaken by Hatch Innovation Services.

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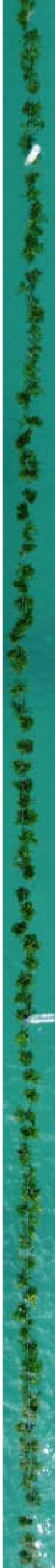

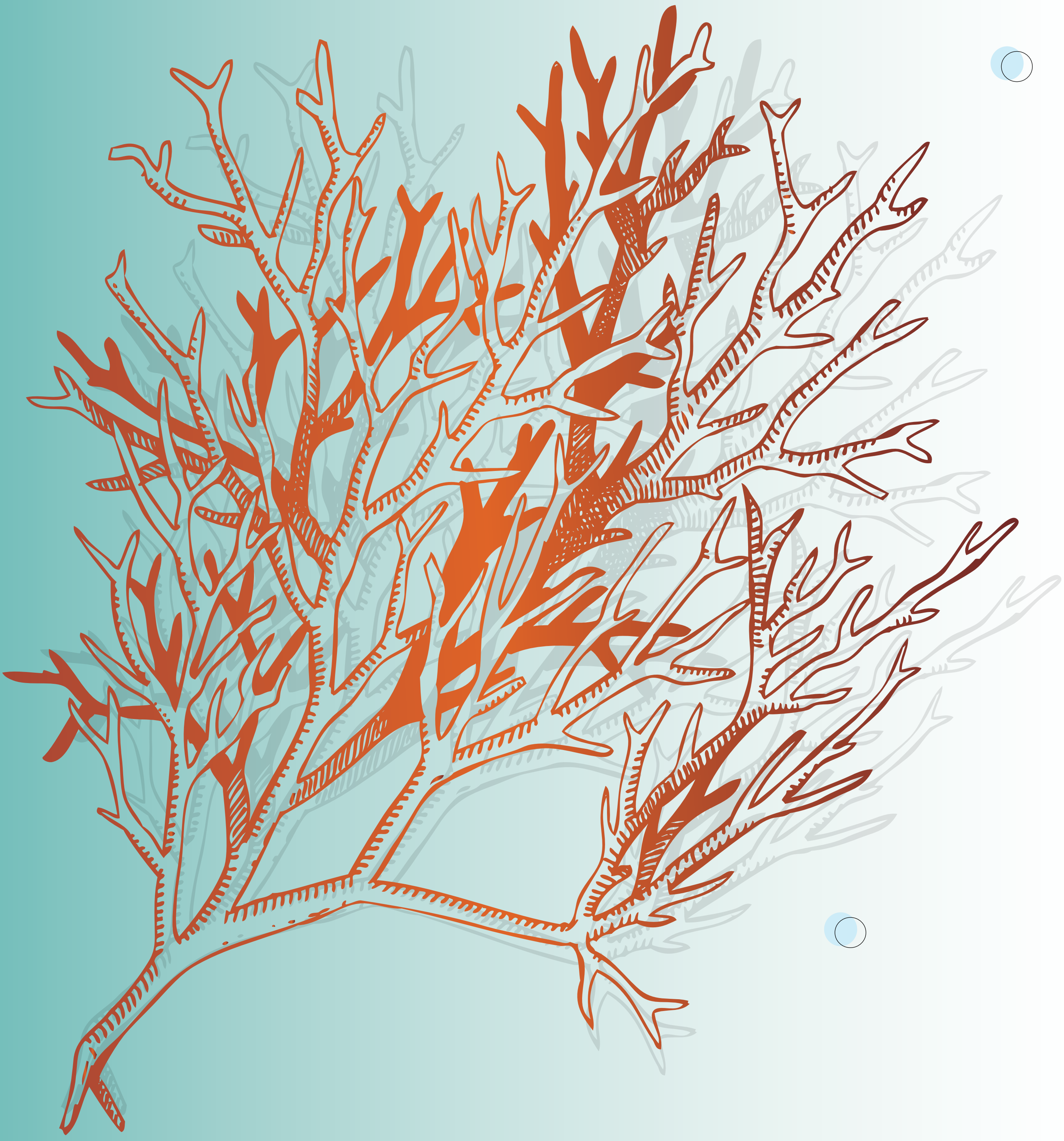

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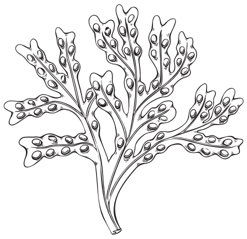


EXECUTIVE SUMMARY

With its ability to sink carbon, sustain marine biodiversity, employ women, and unlock value chains, **seaweed farming demonstrates how development, climate, and nature work together to generate value and uplift communities**. Seaweed farming can help build a world free of poverty on a livable planet and has enormous growth potential. **This report has identified ten global seaweed markets with the potential to grow by an additional USD 11.8 billion by 2030** (Figure A). Yet, much of the seaweed sector's value remains untapped - it has clear growth potential beyond its current markets. Today, most farmed seaweed is used for direct human consumption, as fresh feed in aquaculture, or as hydrocolloids. However, seaweed-farmed products may be able to displace fossil fuels in sectors such as fabrics and plastics; can provide ecosystem services, such as carbon sequestration and nitrogen cycling; and can generate socioeconomic benefits in fragile coastal communities. Further, the market is currently dominated by a handful of Asian countries, which produce 98 percent of farmed seaweed by volume globally. Opportunities for growth in new regions and applications are high.

Aims and methodology

The **Global Seaweed New and Emerging Markets Report 2023** provides an analysis of the commercial opportunities for new high-growth seaweed market applications that could increase the scale of seaweed cultivation and enhance value-added seaweed processing. The report assesses realism and readiness-to-scale of technologies needed to grow more seaweed, extract increasingly valuable compounds, and create quality products for a range of markets. It assesses the potential for the industry to provide optimal socioeconomic and environmental benefits and guide entrepreneurs, investors, and policy makers towards ensuring the seaweed sector fulfills its potential now and into the future.

The report focuses on **10 relatively new and emerging seaweed applications** that have the greatest market opportunities outside the established agar, alginate, carrageenan, food and aquaculture feed sectors. It examines the ecosystem service side of the seaweed sector, providing case studies from emerging projects, along with predictions relating to whether – and how – these services could one day be monetized.

Information was gathered through interviews with key players in the sector, supported by scientific literature and market data. The interviews covered a range of topics including the applications that present the greatest opportunities for seaweed; when seaweed-based products are likely to become cost-competitive; and the challenges the seaweed sector needs to overcome.

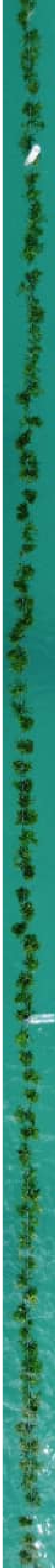
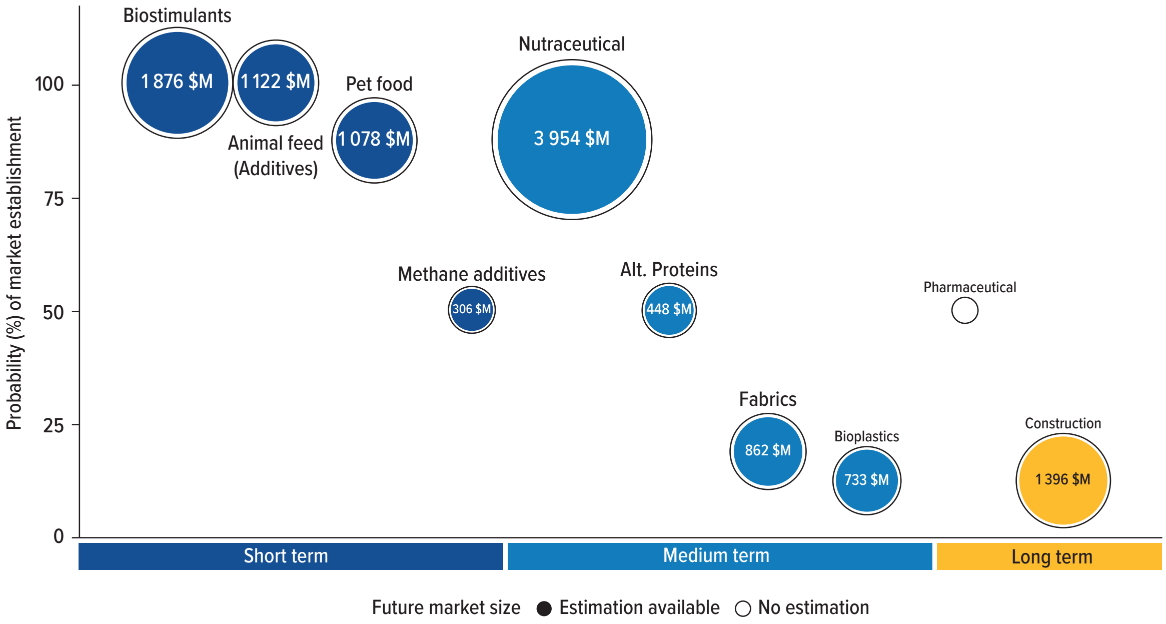


FIGURE A: **Predicted seaweed market size by 2030 ($ millions) with chance of market establishment indicated by color on a high-level market horizon timeline**



Key findings of this study

Finding 1: The most promising short-term markets for seaweed (beyond conventional market applications) are biostimulants, animal feed, pet foods, and methane-reducing additives.

• Short-term markets (before 2025)

Biostimulants, animal feed additives, and pet food are the most promising short-term markets for seaweed, projected to reach USD 4.4 billion by 2030 (Figure A). Seaweed-based products in these high-growth markets already show competitive value propositions and prices. They also present low processing complexity with no significant challenges to scaling compared to other applications. Animal-feed additives reduce dependence on synthetic products and improve animal productivity by reducing feed conversion ratio. Methane-reducing additives represent a totally novel market and, even though there are significant technological and regulatory challenges, there are more vigorous efforts to overcome these in the short term compared to other markets.

Finding 2: Nutritional supplements, known as nutraceuticals, alternative proteins, bioplastics, and fabrics offer medium -term opportunities.

Medium-term emerging market opportunities (2024–2028)

Nutraceuticals offer medium-term market entry points at high value but with the potential for regulatory hurdles to slow down the development of this market, which is projected to reach USD 6 billion by 2030. Alternative proteins, bioplastics -plastics substitutes from renewable biomass sources- and fabrics are also emerging medium-term market opportunities. Because of the challenges they face from significant production costs, prices, and functionality, these markets will need to achieve significant improvements in the cost and availability of seaweed, or else find only niche use cases in the future.

Finding 3: Pharmaceuticals and construction offer long-term opportunities.

Long-term emerging market opportunities (after 2028)

Pharmaceuticals are thought to offer a long-term market opportunity, but with significant regulatory challenges and a high cost of product development. Due to many complex assumptions and lengthy approval times, projections on the market value for pharmaceuticals are unreliable. Construction, such as for building materials, may present a long-term emerging market **projected to reach USD 1.4 billion by 2030** but more likely as a niche application, or through waste valorization in processing seaweed for other applications.

Finding 4: To fully realize its potential, the industry will need to overcome several key issues, including the availability of seaweed, pricing challenges, and regulatory barriers.

Beyond application forecasts, a major challenge across all markets is the **availability of seaweed** because of current limitations in volume, consistency, and the quality of the supply. Current main markets, including seaweed for human consumption and hydrocolloids, are growing consistently and any new markets will have to compete with these established supply chains. This emphasizes the need to significantly increase primary production of seaweed.

In addition, the more the application competes with commodity or commodity-derived products such as plastics or construction materials, the higher the **challenge of developing competitive price levels** for seaweed.

To overcome this, **biorefinery** development presents opportunities to obtain an economically feasible process by deriving several products from a single input of seaweed. However, **competition between markets** that are based on the same compound is expected, and producers will likely switch to the higher-value markets once accessible, reducing the size of previously established markets.

Regulations will also play a significant role in the trajectory of the markets assessed and will have to be analyzed on an individual basis.

Finding 5: The climate and environment benefits of seaweed farming will help drive growth as interest in "green" products continues to increase

Overall, a major driver for most of these potential emerging markets is the "green" benefits of seaweed, and many product developers have expressed a **reliance on sustainability premiums** to generate profits.

Credit schemes relating to **ecosystem services** could potentially improve the business case for seaweed-based products, but require robust monitoring, reporting and verification before they can be widely established.

Finding 6: Ecosystem services offering environmental benefits can boost green economic growth potential

The current focus for seaweed cultivation is **provisioning services**, which relate to material benefits produced by natural ecosystems that can be extracted directly from nature to meet basic human needs. However, macroalgae provide a range of other ecosystem services that moderate, regulate, or support the natural world that have not been fully commercialized or leveraged. Multiple organizations have submitted proposals for blue carbon credits using seaweed. Based on this, it is possible that internationally recognized credit certifications for blue carbon seaweed projects will be available by 2025.

The scale-up of land-based bioremediation operations that can remove or degrade contamination, pollution, and toxins from soil and water to restore land, are expected over the next 12 months, and more attention is shifting toward the **bioremediation potential of ocean farming and macroalgae-based, integrated, multi-trophic aquaculture (IMTA)**.

Several stakeholders suggested that **biodiversity enhancement** could become one of the more important ecosystem service attributes of seaweed farming and restoration over the next decade. Nevertheless, there are some critical challenges to address for these applications: including insufficient measuring, reporting, and verifying; slow certification procedures; a lack of awareness; and a lack of alignment between members of the scientific community.

Conclusion

The seaweed sector has clear growth potential beyond its current markets and can help shape a world free of poverty on a livable planet. Enhanced seaweed production and improved value chains can contribute to meeting at least nine of the 17 U.N. Sustainable Development Goals (SDGs). For example, seaweed farming can sink carbon, sustain marine biodiversity, and employ women. At a time when global resources are increasingly overstretched, it is particularly important that the world makes the most of those resources – such as seaweed – that can both be swiftly regenerated and potentially help to regenerate the ecosystems that support them. Seaweed farming in new markets and with new applications can support development, climate, and nature work to generate value and uplift communities.

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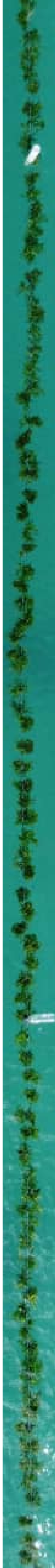


1

INTRODUCTION

Although seaweed has been cultivated for decades in parts of Asia, there is growing support for producing a wider range of seaweed species in a broader range of geographical locations. In time, it is hoped, these can be used for a wider selection of seaweed-derived products in multiple industries. However, many of the uses currently being touted for seaweed products are still in their infancy and require further research and investment before their real potential can be ascertained.

One main reason seaweed farming is gaining popularity is that both cultivation and processing can bring a range of socioeconomic benefits, particularly in coastal communities where many traditional jobs – such as fishing – are in decline.

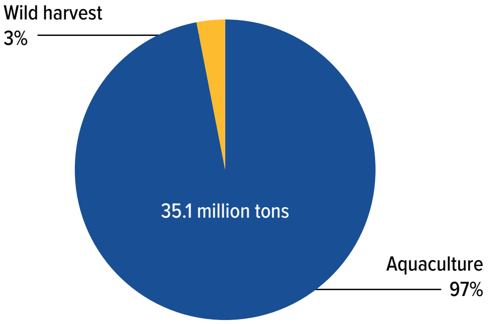
From an environmental perspective, seaweed cultivation can fix carbon, improve water quality by absorbing excess nutrients such as nitrogen, provide a habitat for a variety of beneficial organisms, help to prevent coastal erosion, and provide a suite of other ecosystem services.

Meanwhile the use of farmed seaweed can have indirect benefits by mitigating or displacing more resource-intensive components – in particular fossil-fuel based ones – in a range of industries.

1.1. The current state of seaweed production

The latest State of World Fisheries and Aquaculture (SOFIA) report from the Food and Agriculture Organization of the United Nations reported total global algae production to be 36 million tons wet weight in 2020 (FAO 2022b). This includes both wild-harvested and farmed seaweed and microalgae, although the microalgae volumes are under 100,000 tons wet weight and therefore less relevant.

FIGURE 1: Global production of algae



Source: FAO (2022b).
Note: The figures refer to the proportions of wild-harvested and aquaculture-based algae production of the 36 million tons harvested in 2020.

Although commercial seaweed aquaculture started in earnest only about half a century ago, the production volumes have grown rapidly and tripled in the last 20 years. With wild seaweed resources reaching their limits for sustainable harvesting volumes, the future growth of the industry will rely on farming.

Only a very small number of seaweed species are currently used for commercial purposes. Ninety-five percent of current seaweed volumes comes from the *Saccharina*, *Eucheumatoid*, *Gracilaria*, *Pyropia* and *Undaria* species groups. The dependence on these genera has gradually increased in the past 20 years.

FIGURE 2: Volume growth of seaweed production 2000–2020, in tons wet weight, by species group

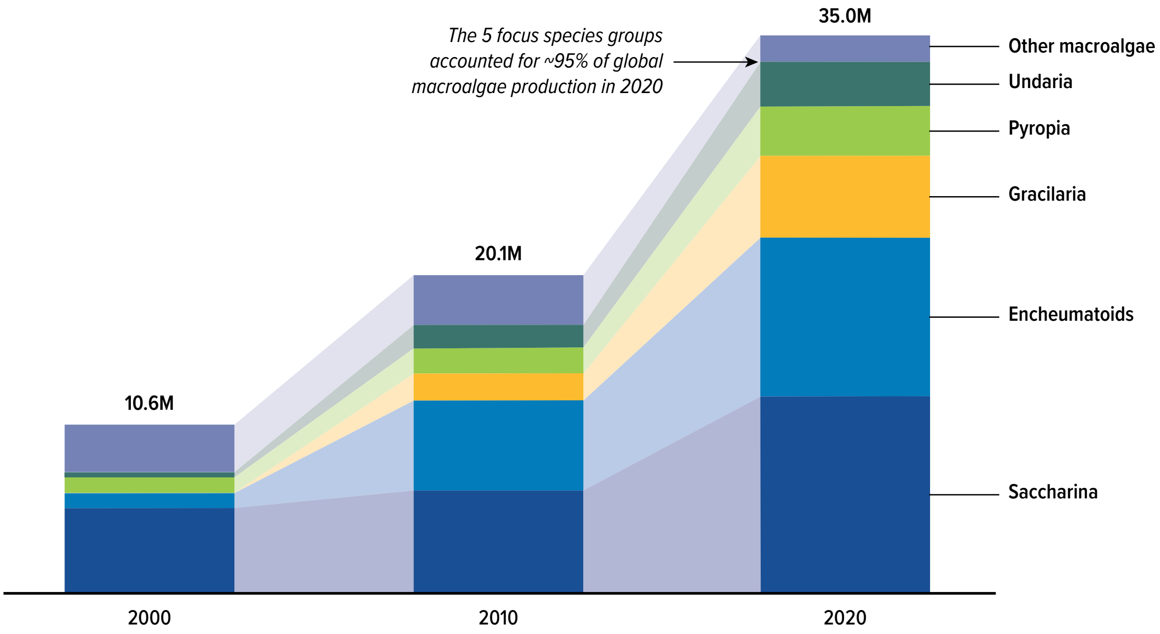
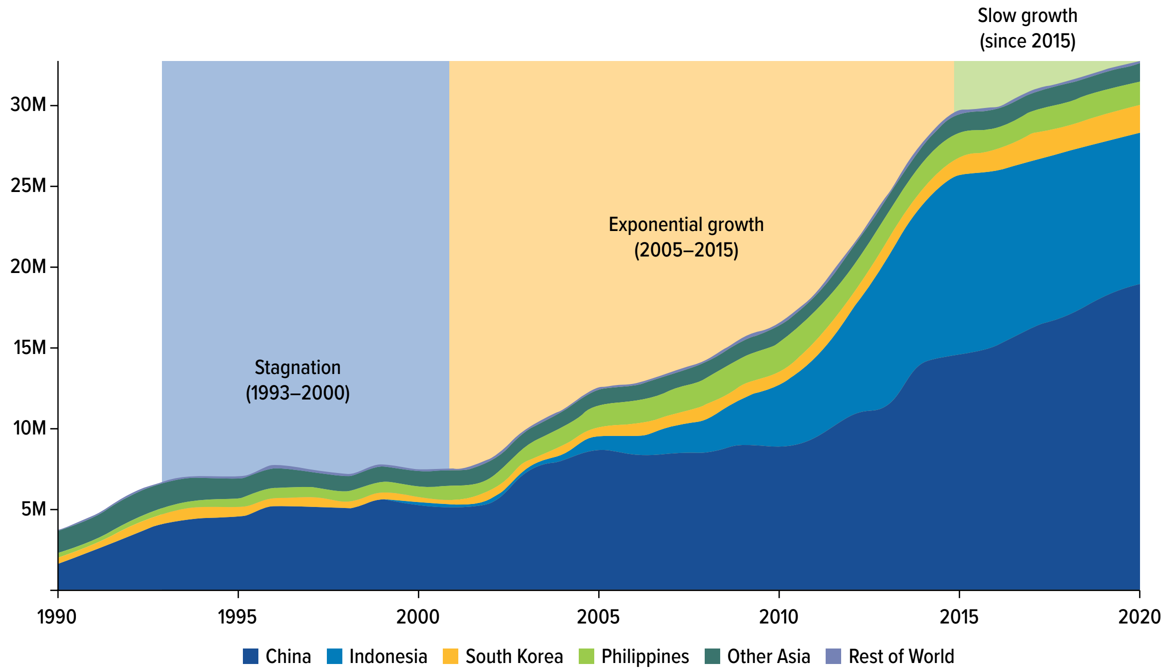


Chart: Hatch Innovation Services
Source: FAO Fisheries and Aquaculture
Created with Datawrapper

Geographically, global seaweed production currently depends on a small number of East and Southeast Asian nations, where commercial farming began more than 50 years ago. Both in volume and value, Asian producers dominate the market, with over 98 percent of market share. The two largest producers, China and Indonesia, supply 56 percent and 27 percent of farmed seaweed by volume, respectively, followed by South Korea and the Philippines, which both produce 4 percent each. Countries outside Asia combined produced less than 2 percent of the total volume of farmed seaweed in 2020.

FIGURE 3: Global seaweed production volumes 1990–2020 in key countries, in tons wet weight



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Source: FAO (2022a)

Between 2015 and 2020, the growth of global seaweed aquaculture slowed in most regions. A recent assessment by Hatch Innovation Services of the state of seaweed farming in the main producing regions suggests much lower production overall than previously – and stagnating or decreasing volumes in the coming years – in some of the top seaweed-producing regions (Hatch Innovation Services 2023). This is primarily due to significant challenges the conventional farming sector is facing.

Climate change is creating shorter growing seasons and warmer waters, leading to a decrease in commercial seaweed yields. Seaweed farming in Asia is almost entirely reliant on human labor, yet in East Asia fewer people are available to work in the sector, while in Southeast Asia, the levels of efficiency are static and primarily restrained by the lack of good-quality seed supply.

Apart from these challenges, on-the-ground research reveals that, because of data reporting issues, the reported official production volumes in some of the leading seaweed-producing countries are not realistic and that seaweed production in Asia is in fact much lower than officially stated (Hatch Innovation Services 2023).

Another key discovery during this research is the lack of innovation in the established seaweed farming regions, with very few novel cultivation or processing methods encountered (Hatch Innovation Services 2023). This situation suggests that – despite the groundswell of support for seaweed production and processing in the West – the Asian blueprint is not necessarily a recipe for success in other regions.

1.2. Seaweed production: A Western perspective

More recently, there is a substantial focus on seaweed farming in North America and Europe, both within the public and private sectors. For example, the European Union considers seaweed farming to be a key pillar of its blue bioeconomy strategy (European Commission 2022). In 2022, there were approximately 200 startups in Europe, North America, Australia and New Zealand working on seaweed (Hermans 2023).

However, production volumes of farmed seaweed in North America and Europe are just in the hundreds of tons, and growing only slowly. Similarly, Africa and Latin America have high potential to use their long coastlines and Exclusive Economic Zones for seaweed production, yet the volumes are only increasing very slowly in these regions too.

1.3. Current seaweed markets

In Asia, seaweed has been part of the human diet and food culture for centuries. This has been the primary driver to establish supply chains for temperate seaweed species in East Asia. Besides its nutritional value, seaweed has grown even more popular in recent years in Asian cuisine because it adds unique textures and flavors to food (Rioux *et al*. 2017). These features, combined with the fact that most species have no intrinsic toxins, make seaweed a very attractive product for the food industry (Cai 2021).

Although the majority of seaweed biomass is used for direct human consumption, seaweeds are also commonly fed directly to abalone, sea urchin, and other low-trophic species in aquaculture.

The third major use of seaweeds today are as food additives. Seaweed-derived hydrocolloids are used for their gelling, stabilizing, and thickening functionality. Seaweed contains a large proportion of carbohydrates as structural, storage, and functional polysaccharides. These consist of bonded sugar molecules. Phycocolloids or hydrocolloids are a heterogeneous group of long-chain polymers (polysaccharides and proteins) commonly found in seaweeds. The most important ones commercially are alginates, agar, and carrageenan. They are primarily used in a variety of food industry sectors, including the production of bakery, dairy, and meat products.

Alginate, the most abundant polysaccharide in brown algae, makes up as much as 40 percent of the dry weight of brown seaweed (Rosenboom *et al.* 2022). Currently, alginates are used as gelling agents in the food industry and as a stabilizing and thickening substrate in the beverage, cosmetic, paper, pharmaceutical, printing and textile sectors (Aswathi Mohan *et al.* 2022), but research is under way to develop garment-ready textiles made from alginate. The most commonly used species for the extraction of alginates are from the *Ascophyllum, Durvillaea, Ecklonia, Laminaria, Lessonia, Macrocystis* and *Sargassum* genera (McHugh 2003). Most of the volumes used for alginate production are harvested from wild stocks. The forms of alginate used in the food industry are alginic acid, sodium alginate, potassium alginate, ammonium alginate, calcium alginate and propylene glycol alginate, and they respectively carry the European additive codes E400 to E405 (Featherstone 2015).

Agar is a mixture of polysaccharides composed of agarose, the gelling component, and agropectin, which has a low gelling capacity (Armisén and Gaiatas 2009). It has various applications in the pharmaceutical, food, and cosmetic sectors as a hydrocolloid, with 90 percent of production used in the food industry. Agar is the major cell wall constituent of certain red seaweeds, especially from *Gelidium* spp. *Gelidiella* spp. and *Gracilaria* spp. (Kaliaperumal 2003). Most of agar's commercial production comes from cultivated seaweed (FAO 2018). Agar is defined as a strong gelling hydrocolloid from marine algae, it is a food additive considered as Generally Recognized as Safe (GRAS) by the US Food and Drug Administration (FDA). In Europe it is classified as an E406 additive (Armisén and Gaiatas 2009).

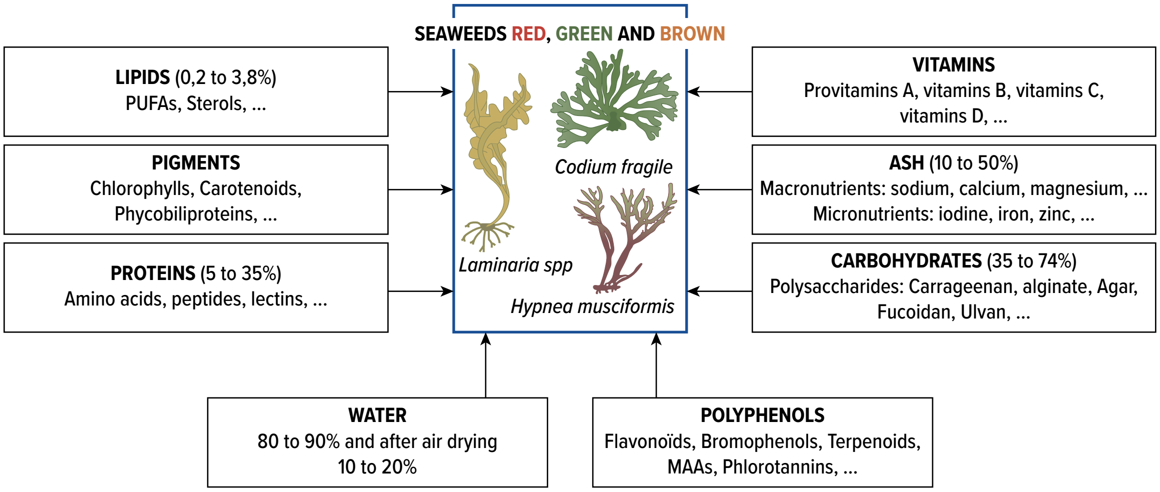
Carrageenan is a hydrocolloid, similar to agar, that can be extracted from the cell walls of red seaweeds, where it represents between 30 and 80 percent of the cell wall constituents and acts as a structuring agent (Venkatesan, Anil and Kim 2017). It has various applications in the pharmaceutical, food and cosmetics sectors, where several carrageenans, differing in their chemical structures and properties, have different uses. The carrageenans of commercial interest are called iota, kappa and lambda. The main supply of carrageenan comes from eucheumatoid aquaculture in tropical regions, predominantly Indonesia and the Philippines. For the food industry, carrageenan is labeled as E407 in the European Food Additives Classification (FAO 2018).

Beyond industrial hydrocolloids, it has been demonstrated that seaweed polysaccharides – polysaccharides obtained from the cell walls of seaweed – provide health benefits. Fucoidans, mannitol, laminarin and ulvan are four examples that are used in specific applications for their unique bioactive properties (Kraan 2012).

Seaweeds can provide raw materials for a wide range of applications due to their diverse composition. Whether red, green or brown, macroalgae have a multitude of compounds of different uses in varying proportions, depending on the species. In general, seaweeds are rich in carbohydrates (which make up 35 to 74 percent of their dry weight) such as polysaccharides; contain several minerals such as iodine, iron, zinc and calcium; lipids (0.2 to 3.8 percent) such as polyunsaturated fatty acids (PUFAs); proteins (5 to 35 percent); essential amino acids; pigments; polyphenols; vitamins and other nutrients.

Their chemical composition values vary significantly, according to many factors – including species, growth stage, climatic conditions, water temperature, and the concentration of nutrients in the water. The general compositions of seaweeds are presented in the following figure, based on approximations taken from literature reviews.

FIGURE 4: General composition of red, green and brown seaweeds



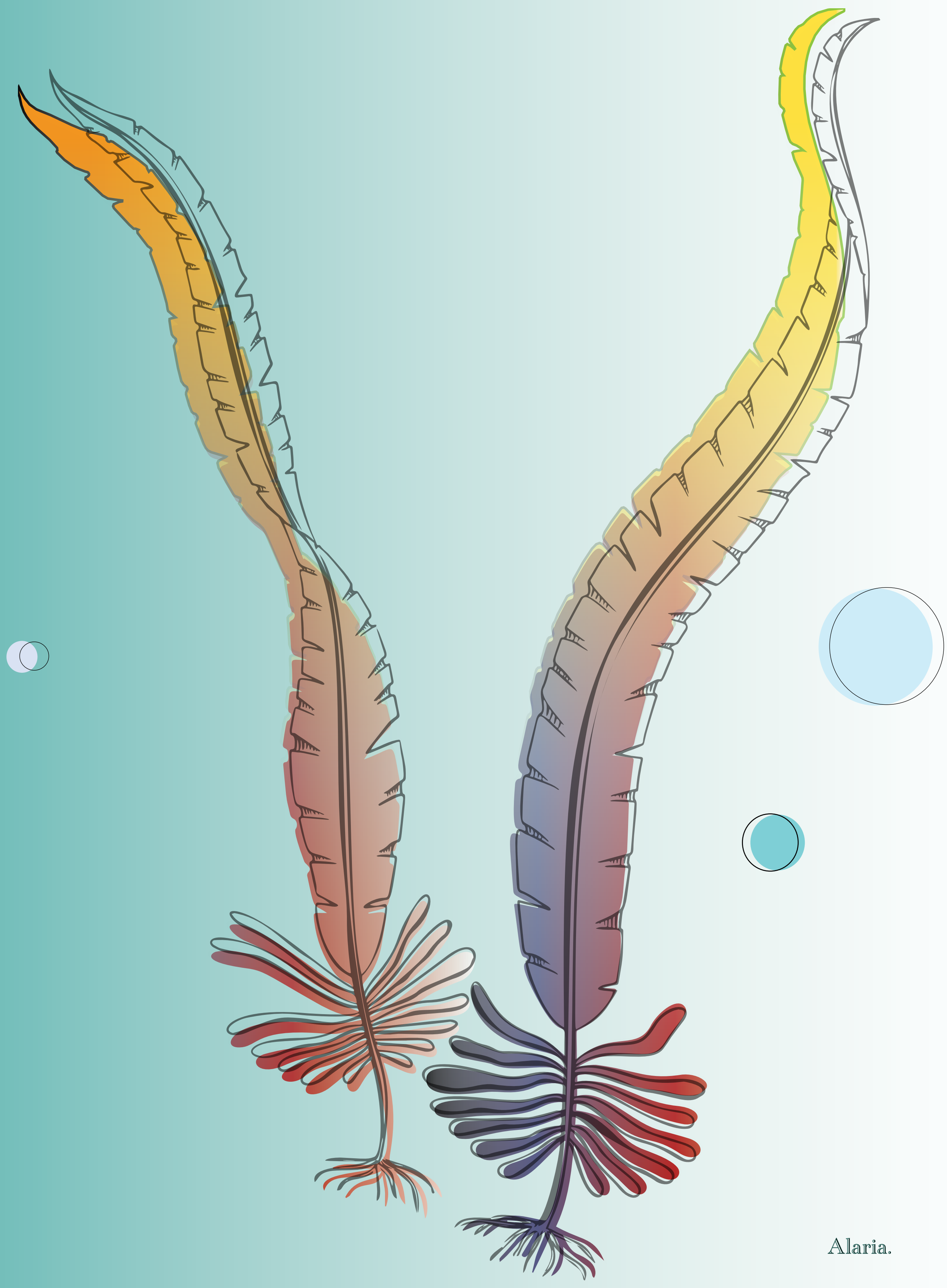
Source: Based on Ito and Hori, 1989; Kim, 2011; Peng et al., 2015.

1.4. New and emerging applications of seaweed

More recently, however, the applications for seaweeds have expanded significantly – from the traditional use for human consumption to a much broader variety of applications. Beyond current applications, seaweed-based compounds are being explored for their use in various new and emerging markets. Such new valorization opportunities could drive further the cultivation of seaweed and its associated environmental and social benefits.

This report intends to deliver a realistic analysis of the value seaweed does provide – and could provide – to new and emerging markets; highlight existing challenges ahead of a widespread adoption of seaweed-based solutions in those markets; and give an estimate of the potential for seaweed in these markets.

The findings of the report are expected to help public and private sector decision makers, entrepreneurs, and investors to make more informed decisions on how to drive the growth of the global seaweed industry.



Alaria.

2

METHODOLOGY

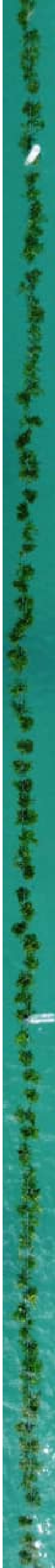
The research that forms the basis of this report involved the identification of relevant industry sectors for seaweed market opportunities (Phase 1), followed by a detailed assessment of those selected application areas (Phase 2) and a market forecasting exercise (Phase 3).

2.1. Phase 1 – Identification of relevant industry sectors

A combination of an initial literature review, conversations with industry experts, and learnings from a four month in-field study provided the list of industry sectors for further analysis (Phase 2) in this report. The aim was to identify markets that display significant growth potential, high environmental and socioeconomic impact potential, and low levels of existing commercialization in order to discover new and emerging market opportunities.

During this first phase, over 120 existing and potential applications of seaweed were collated. A prioritization exercise was then applied to select the most promising new and emerging markets, looking at the following characteristics:

1. Evidence of strong market size potential and growth forecasts. This metric looked at both seaweed-specific market figures (where available) and non-seaweed specific market figures. These included:

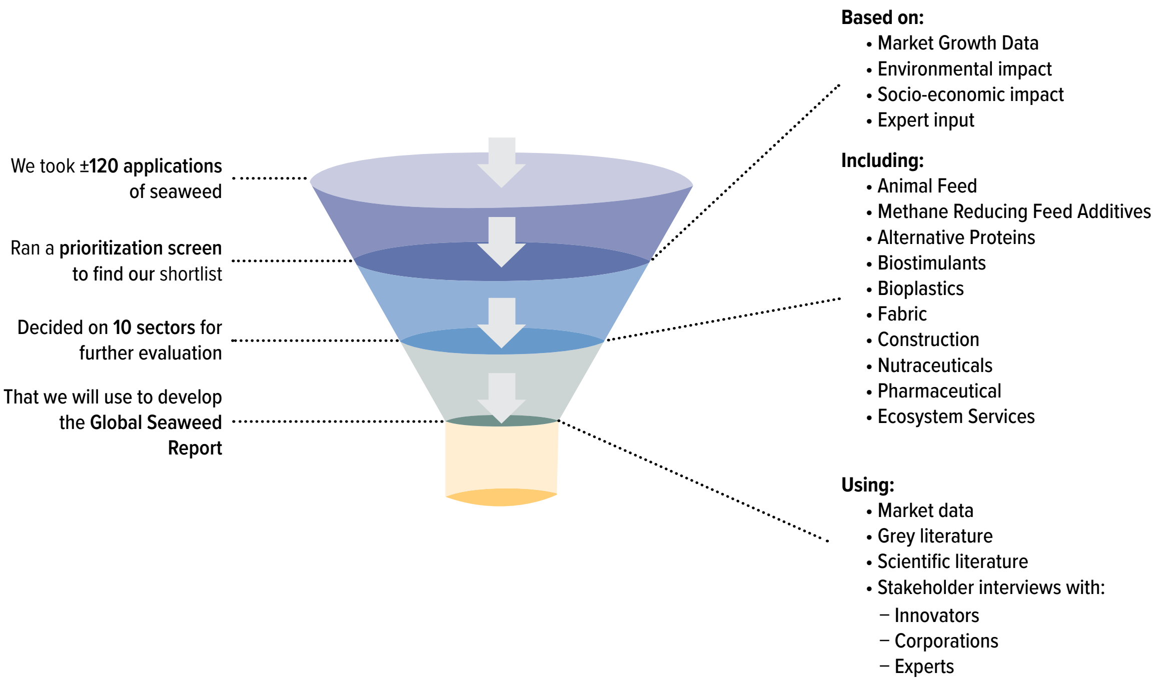


    - The latest figures on seaweed-specific market size and market growth, using Compound Annual Growth Rate (CAGR); the number of seaweed-based products or applications in the market; and their respective values.
    - Non-seaweed-specific market size from 2021 or 2022 – in Phases 2 and 3, which are referred to as the total addressable market (TAM) and CAGR.

   Since the market size or forecasting figures for many seaweed-specific applications were not available, because of the early stage of their market development, non-specific market growth data was used as a signal for the potential growth of this market.
2. Evidence of environmental impact. This includes direct environmental impact of supply and cultivation practices, as well as the potential for displacing greenhouse gas-intense (GHG-intense) products and emissions reduction.
3. Evidence of feasibility. This metric took into account any available information on the level of technological readiness, operational factors, and production costs of potential products and applications.

Based on expert opinions, the markets were then scored to establish a shortlist to be covered in this report. Given that the focus of this report is on market opportunities, significant weighting was given to evidence of strong market size and growth forecasts as indicators of market attractiveness.

FIGURE 5: Process for selecting seaweed applications in this report



It was not possible to be exhaustive in the choice of applications. Apart from the prioritization factors listed above, this report gives priority to applications that are likely to see further development in the coming years. The ranking process excluded existing markets – such as cosmetics and food applications – that use agar, alginate and carrageenan as these already have industrialized supply chains.

Findings from an extensive study carried out by Hatch Innovation Services on the supply side of the seaweed industry provided relevant information to understand what volumes are available and what markets can be excluded from this report (Hatch Innovation Services 2023). In addition, the study included visits to Asian companies working on new products and applications, providing relevant additions to the list of potential market applications. A compilation of the data and analysis is available at www.seaweedinsights.com.

2.2. Phase 2 – Deep dives into selected seaweed application areas

During the second phase, the 10 selected industry sectors were assessed in detail with regard to their potential for seaweed-based applications. Due to the lack of publicly available data on prices and volumes for these applications, data-gathering focused on interviews with key stakeholders to understand the primary market drivers, dynamics, competition, and outlook for these sectors.

During this phase 133 interviews were conducted with leading corporations, innovators and experts (Table 1). Where available, market data points were gathered and informed the analysis. In total, more than 300 sources – including scientific literature, grey literature and market reports – were analyzed.

TABLE 1: Overview of interviews with stakeholders from each market sector

Industry sector	No. of interviews
Ecosystem Services	20
Animal Feed	16
Nutraceuticals	12
Construction	10
Methane Reducing Additives	10
Alternative Proteins	9
Pet Food	9
Bioplastics	9
Fabrics	9
Biostimulants	9
Alternative Proteins	9

Each analysis aims to provide an understanding of the current state of the market, synthesize market sentiment from leading operators within that sector, and provide insights into the main challenges and opportunities present for each emerging or new seaweed application. This in turn influences the market outlook, which presents a view on how long it will take to have widely available, commercially competitive products. The analysis aims to outline the opportunities to expand and develop existing and future supply chains.

A further section is provided on the current state of several ecosystem service applications, which are seen as important drivers of the seaweed industry. This analysis takes on more of a case study format, with a particular focus on blue carbon, bioremediation, methane reduction, and biodiversity enhancement – areas of heightened interest within this space. Market outlooks were influenced by stakeholder sentiment, and by an analysis of the available literature.

2.3. Phase 3 – Market forecast exercise

This part of the analysis intends to forecast seaweed-specific market sizes for new and emerging applications. It looks at the serviceable addressable market (SAM), which describes the share of the total addressable market (TAM) that could be made up of seaweed-based products.

It aims to provide an indication of the growth potential, and consequently, the opportunity this market presents for a business. This report used the year 2022 as a base and 2030 as a future horizon for its projections.

The foundation of this market forecasting model provides a number of non-seaweed-specific (A, B, C) and seaweed-specific (D, E, F, G) data points (see Table 2). These inputs were either based on existing figures from secondary sources as part of the data collection process or calculated from the authors' assessments (see Table 2).

TABLE 2: Foundation of this market forecasting model

	Non-seaweed-specific inputs	Seaweed-specific inputs
Secondary source	A = Total addressable market Size (TAM) in 2022 ($ billion) C = Growth rate of TAM (percent CAGR)	B = Seaweed-specific market size – SAM in 2022 ($ billion)
Calculated	D = TAM in 2030 ($ billion)	E = Relative seaweed market share in 2030 (percent) F = seaweed-specific market size – SAM in 2030 ($ million)

Calculation of the seaweed-specific market size in 2030 (F)

The seaweed-specific market size in 2030 (F) for seaweed-based products in the total addressable market (TAM) (D) was derived by:

*The seaweed-specific market size in 2030 (F) = total addressable market in 2030 (D) * relative seaweed market share (E) / 1000*

The relative seaweed market share (E) for seaweed-based products in the total addressable market in 2030 (TAM) (D) was derived by:

*Relative seaweed market share (E) = SAM Score (G) * maximum achievable market share (H)*

The SAM score (G) consisted of the unweighted average in percent of a scoring of the following parameters:

- The value proposition of the seaweed-based products
- The competitive pressure from alternative products
- The presence of challenges and the likelihood that they will be overcome

Each seaweed application was scored along all three parameters, according to the scheme presented below. The information gathered on each application provided the authors with the foundation to make scoring decisions.

TABLE 3: Scoring scheme

Seaweed's value proposition	1 = Seaweed has very little value in a specific market.	5 = Seaweed meets all demand/ customer needs.
Competitive pressure from other products/solutions	1 = A lot of equal or better solutions are in the market and/or expected to enter the market.	5 = No solution other than seaweed exists.
Presence of challenges and likelihood of challenges being overcome	1 = Many challenges and low chances of solving challenges.	5 = Almost no existing challenges and a lot of resources deployed to overcome them.

The maximum achievable market share in 2030 (H) was derived by:

$$\text{Maximum achievable market share (H)} = \text{MAX}(-0.071 * \ln(\text{total addressable market in 2030 (D)} * 1000) + 0.8267, 0.01)$$

An assumption was made that the attainable market share by seaweed-based products, independent of their competitiveness, depends on the total market size. Under normal market conditions, the larger a market is, the harder it would be for companies selling seaweed-based products to gain significant market share. Hence the larger the TAM, the lower the maximum achievable market share is likely to be.

Probability of market establishment

Beyond the potential market share calculation, a probability of market establishment was also estimated. This is a relevant control exercise to make sure that the potential is accounted for in realistic terms, also taking into consideration that some markets may be unlikely for seaweed. The presence of make-or-break challenges was therefore assessed by the number and severity of such potential challenges, as well as the likelihood that they will be overcome. If any of these deal-breaker challenges cannot be overcome, they would prevent the market development.

The probability of establishment for each market consisted of the unweighted average, in percent, of a scoring of the following parameters:

- Presence of deal-breaker challenges (number and severity)
- Likelihood of challenges to be overcome

Each seaweed application was scored along both parameters, according to the scheme presented below. The information gathered on each application provided the authors with the foundation to make scoring decisions.

TABLE 4: Scoring scheme

Presence of deal-breaker challenges (number and severity)	1 = Many severe deal-breaker challenges	5 = No deal-breaker challenges
Likelihood of challenges to be overcome	5 = Very low likelihood that challenges will be overcome	5 = Very high likelihood that challenges will be overcome

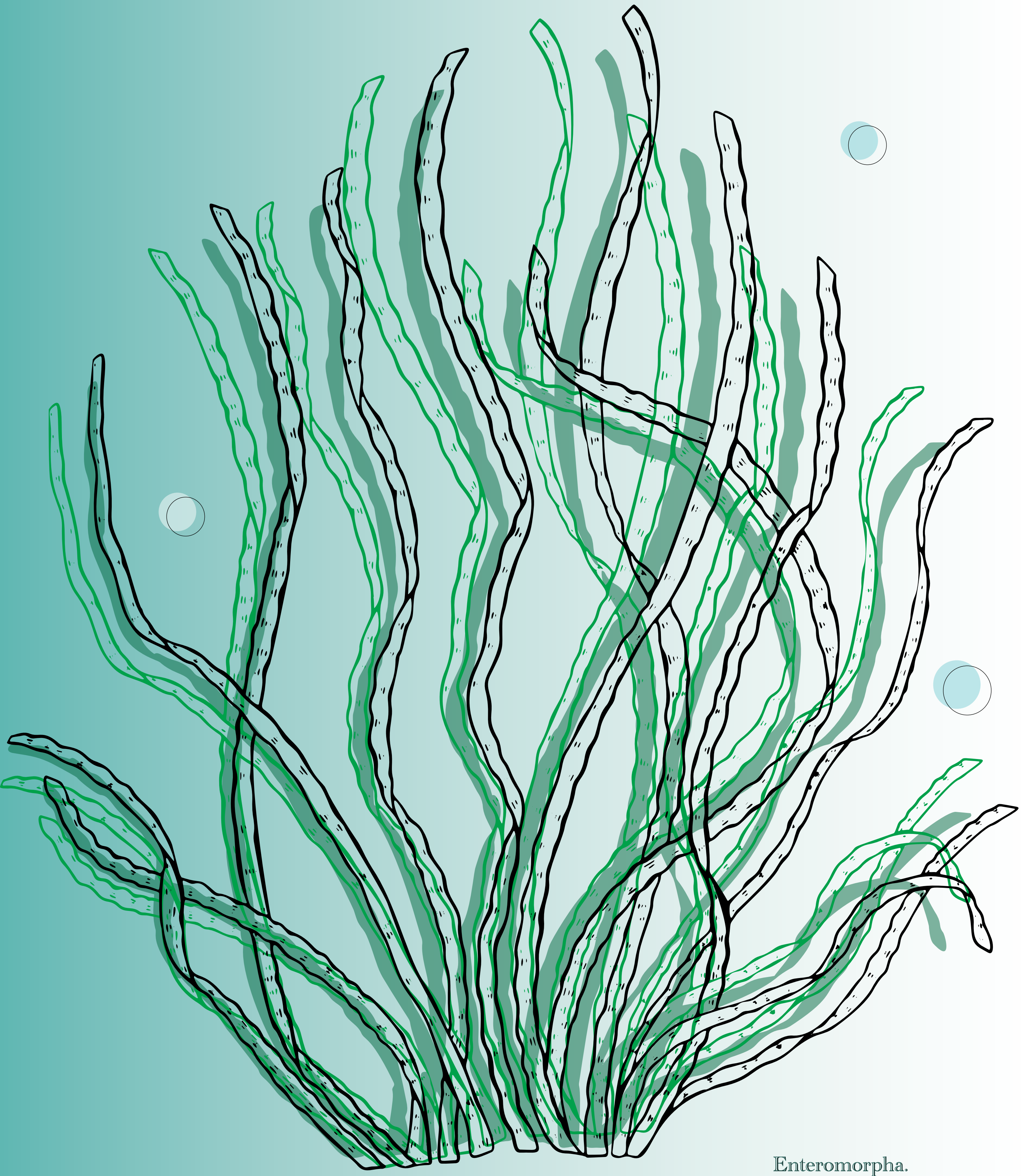
Seaweed-specific market size in 2030 calculations

Figures on the market size and growth rates of seaweed-based biostimulants are already available, so directly applying the CAGR to these figures led to the likely SAM for biostimulants in 2030. However, the pharmaceuticals market was excluded from this exercise because the resulting high value of the SAM might have been misleading, while the assessment would have had to be based on many assumptions at this point.

2.4. Limitations

The following limitations affect the findings and conclusions of this study.

- **Competition between market applications**
  The model does not consider that producers may switch to other markets if those markets become more promising opportunity areas. More on this topic is included in the “Competition between market applications” section of Chapter 3, “Commonalities of emerging market opportunities.”
- **Data availability**
  Although the focus of this study is on the future demand for seaweed-based products, some of the markets covered are at an early stage of development, and sources of public information on market and application data are few. Furthermore, because of differences in the stage of maturity, levels of information varied significantly across the applications assessed in this report. Publicly available reports were not always coherent, and sometimes were even contradictory. In cases where data were limited, additional verified data were obtained through direct stakeholder interviews.
- **Basis for market forecast**
  Due to limited data availability, the presented market forecast exercise should serve purely as a provisional model: the more data that become available on each of these market applications, the more robust the model will become because fewer decisions will be based on assumptions.
- **Sensitivity of the market forecast**
  The nature of the market model implies a high sensitivity of the forecast market size to several factors. Since there is a large variation of product types in each of the markets, it highly depends on which market segment is chosen for the TAM (and similarly, which TAM is chosen will strongly influence the SAM).
- **Dynamic of the market forecast**
  It is important to note that such a score is dynamic and strongly depends on the information available at the point in time the assessment was made – in this case January 2023. Even a few months later, significant market developments in a sector could already lower or raise the score for one of the parameters and, consequently, impact the overall score for this market.



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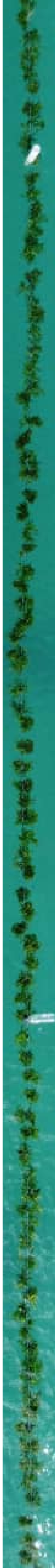


3

COMMONALITIES OF EMERGING MARKET OPPORTUNITIES

This chapter describes common findings across the 10 applications of seaweed assessed during the report's in-depth review. Each of the following chapters will explore one specific new or emerging market and will focus on the market-specific findings, while referring to shared commonalities with the other markets where applicable.

FIGURE 6: The seaweed applications investigated in this report

- Pharmaceuticals
- Nutraceuticals
- Biostimulants
- Alternative proteins
- Animal feed
- Methane reducing feed supplements
- Pet food
- Bioplastics
- Fabric
- Construction

3.1. Seaweed as a third-generation feedstock

In many markets, seaweed competes with products that contain terrestrial crops as their primary raw materials. The raw materials in all these sectors are referred to as feedstocks, and can be categorized as first-, second-, and third-generation.

First-generation feedstocks are primarily edible crops – corn, soya, wheat, and other agricultural commodities – that are in demand for human and animal consumption. Second-generation feedstocks are non-edible or are by-products of first-generation feedstocks – such as waste from agriculture, forestry and animal processing. Both first- and-second generation feedstocks require cultivation on land intended for food production and so pose a challenge to planetary resources.

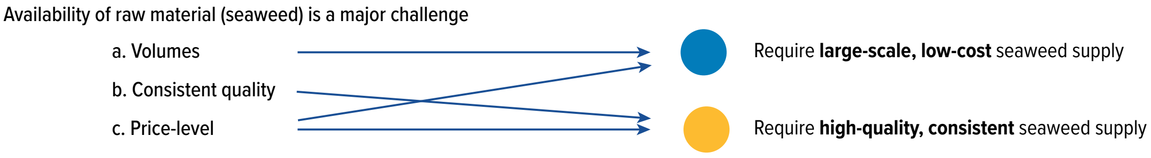
The most unconventional feedstocks are the third-generation. These do not use arable land. They include macroalgae/seaweed (Coppola *et al*. 2021). As a blue biomass, seaweed does not depend on freshwater or land usage and does not use material that could otherwise be used in the food system. Seaweed grows faster than first-generation feedstocks, is more space-efficient, and does not require the addition of fertilizers. For example, it is possible to grow about 26 tons of seaweed (dry weight) per hectare near-shore, compared to 2.3 tons soya and 5.1 tons corn per hectare of land (Bellona 2017). Due to these attributes, seaweed in many circumstances should be preferable to first- or second-generation feedstocks.

3.2. Common challenges

i. Supply availability

The availability of seaweed is currently a major challenge, especially for new and emerging market applications, which need the right volumes, consistent quality, and affordable price levels (see below). The challenge of low availability was found across all new and emerging market applications and is strongest where market value can be derived only from a specific species of seaweed, or one that is currently available only in small volumes. By contrast, some market applications – such as pet food, biostimulants, and animal feed additives – can potentially be derived from a multitude of different species and supply chains, and so have fewer challenges.

FIGURE 7: Supply availability requirements and limitations



Volume

Seaweed sourcing for novel uses presents a challenge, as much of the existing seaweed volume is already destined for traditional markets such as food ingredients and fresh aquaculture feedstock. To add to the challenge, the production volumes of some major farmed seaweed species are in decline. To cater to markets such as animal feed, pet foods, alternative proteins, fabrics or bioplastics, companies need to order thousands of tons of seaweed.

Seaweed consists of approximately 80–90 percent water, so large quantities are needed to produce significant volumes of dry materials. Shipping seaweed in its fresh state is typically uneconomical because of the weight of the water content. Consequently, most seaweed is pre-processed – typically dried – close to the farm site. This requires further resources and adds to the production costs.

Considering that commercial-scale quantities of seaweed are currently produced only in the major Asian producing countries, the availability of raw material can be a challenge to produce value-added seaweed products in other regions. It is often more efficient for companies to complete the primary processing near the farming locations. There are, of course, markets local to areas of production. However, production facilities will need to be widely distributed to tap into high-value markets elsewhere. Localized processing will enable shorter supply chains, avoiding logistical complexity and reducing costs.

Consistency of supply

Another challenge is the inconsistent availability of large quantities of seaweed because of its seasonality. Farmed, temperate seaweed species are generally harvested only in a few months of the year, and it is not possible to store them in an untreated state for long because of their high water content. Further development of pre-processing is required to stabilize seaweed for year-round processing facilities to then increase asset utilization and become economical.

Quality of supply

All seaweeds are challenging raw materials to work with because their compound profiles are influenced significantly by the environment they grow in. Because the environmental conditions vary, the composition of the seaweeds may change. Seasonal variations have a major effect on the bio-composition of the seaweed and thus on the quality and availability of particular compounds required for the products and applications discussed in this report. Although quality concerns present a challenge in all seaweed applications, their importance generally increases with the value of the specific application. Active compounds can vary widely in quantity and quality, which is a challenge for applications that rely on specific compounds.

External impurities also impact the quality of seaweed. These include other organisms attached to the seaweed, as well as sand. The risk of external contamination is also high, especially in at-sea growing environments and those post-harvest processes that take place outside.

ii. Cost of supply

The current cost of seaweed is a challenge for most users of seaweed-derived products in this report, except pharmaceutical applications. The more the application competes in large volumes with commodity or commodity-derived products (for example, plastics or construction materials) the higher the challenge associated with raw material and production costs.

Inconsistent supply of seaweed also affects price and availability. At the time of writing this report there is high price volatility in the Asian seaweed market and high costs in terms of production. Prices for farmed seaweed feedstock vary significantly by species, origin, and condition (for example, wet, dry, or cut). Generally, in 2022, cultivated temperate brown kelp species from China and South Korea sold for around $400–500 per ton fresh weight at the farm gate. In Indonesia, farm-gate prices for cultivated tropical red seaweeds started at around $300 per dry ton for *Gracilaria*, and $500 per ton dry weight for Spinosum (*Eucheuma denticulatum*) (Seaweed Insights 2023).

The costs of all operational stages – cultivation, harvesting, processing, and transportation – need to be taken into consideration. It is often suggested that economies of scale will bring down the cost per ton of harvested seaweed, but with the cost of production mostly driven by human labor, farm processes will have to become significantly more automated to allow cost-efficient, large-scale production. Also, the impact of large-scale farms on the surrounding ecosystems and on marine nutrient levels have yet to be comprehensively analyzed, so their sustainability is not yet certain.

Although the wild harvesting of natural seaweed (especially in forests of kelp species) can be cheaper than cultivation, the available capacity from wild sources is not enough to meet the volumes required, even for current consumption. In most regions, concessions to harvest wild seaweed beds are limited to ensure environmental sustainability.

BOX 1: A NOTE ON BIOREFINERIES

With current raw material prices too high to produce price-competitive goods for many of the new markets, much emphasis has been put on processes that allow higher valorizing of the biomass. In this context, the **biorefinery model** is important because of its potential to create various products from a single source of feedstock. Most applications that were analyzed highlighted this method as a key opportunity to bring down raw material costs and improve the business case, as several products can be derived from one processing facility.

In biorefineries, the process of separating or extracting one (high-value) component is often done in stages (that is, cascades) and can lead to additional products – such as biostimulants, bioplastic materials, or animal feeds. The processes applied to the seaweed in such facilities involve extraction, fermentation, heating, and maceration.

The possible product range from seaweeds may surpass other feedstocks of comparable bulk and low-input cultivation. However, because of the structural complexity and heterogeneous carbohydrate composition of seaweed's constituent polysaccharides, it is a challenging biorefinery feedstock. Increasing levels of effort are being focused on developing biorefinery processes for seaweed.

iii. Competition

The new and emerging seaweed-based market applications discussed in this report have to compete not only against other solutions in their end markets, but also with other product categories in sourcing seaweed-based raw materials.

Competitive advantage over alternatives in the market

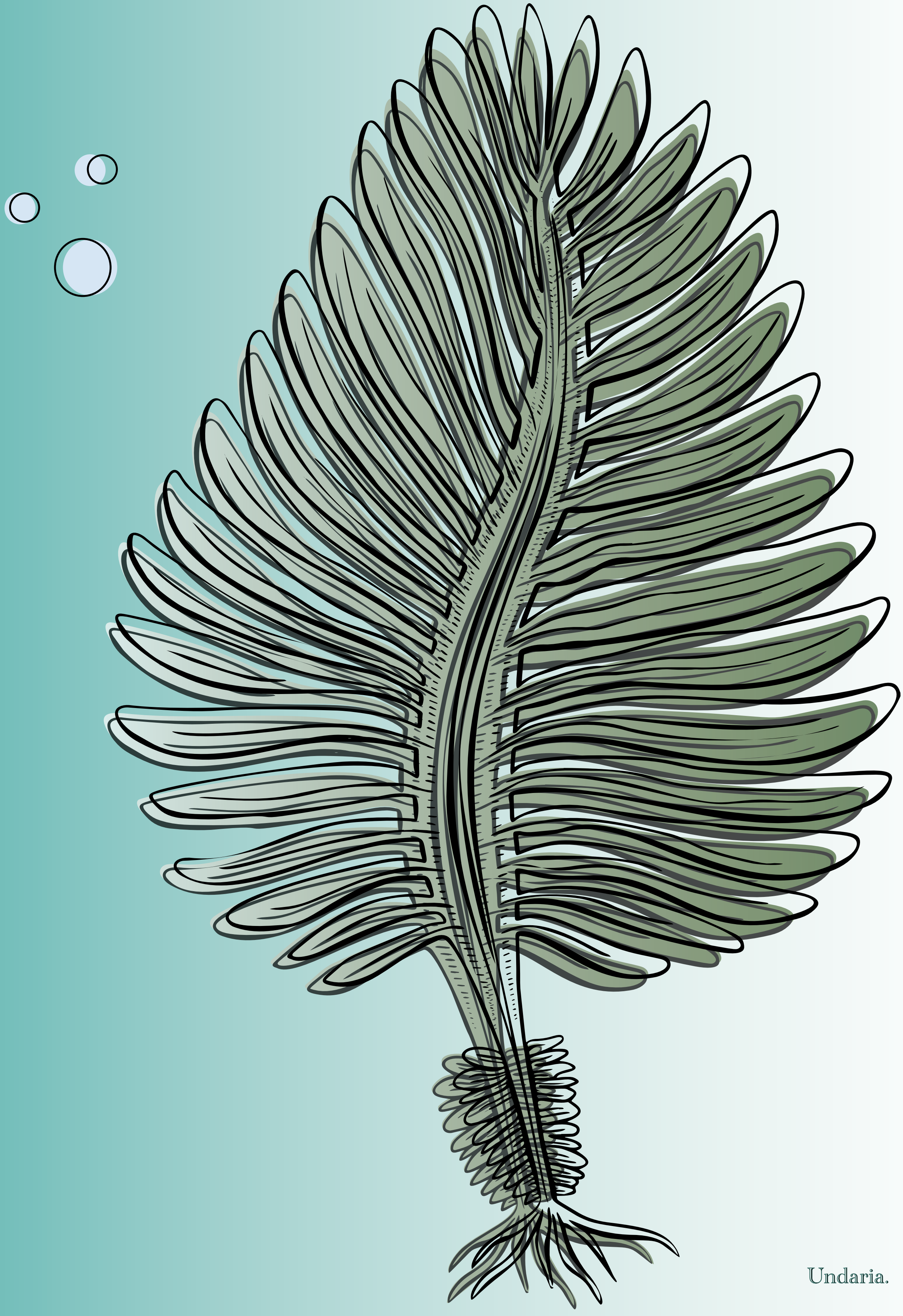
Seaweeds are often highlighted for their low environmental footprint compared to other feedstocks. This may make them more attractive to consumers and could justify a green premium, which would support the growth of new markets. However, without life cycle analyses (LCAs) of each application, it is not clear that the investment required in seaweed supply chains makes them superior to land-based alternatives. In addition, there is a significant risk associated with developing business models that rely on sustainability premiums to be economically viable because consumers often display purchasing behavior that is not in line – or no longer in line – with sustainability objectives they previously stated were especially important to them.

Competition between market applications

Competition also exists between seaweed-based product categories. Different applications of seaweed are often based on the same or comparable compounds and therefore more competition over the supply and usage can be expected. Although feedstock prices vary – according to geography, species, and level of processing – where startups are competing using the same feedstock costs, the incentive often is to create the highest-value product possible.

iv. Regulations

The challenge presented by unclear regulations varies from application to application. It is often unclear under which category seaweed-derived products fall, and therefore how they can be regulated, so products may very well miss out on supportive frameworks and subsidies. Additionally, as with most new applications, many avenues for using seaweed still have significant regulatory hurdles to overcome.



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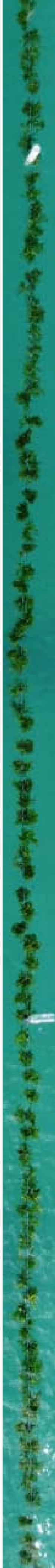


4

MARKET SECTORS

4.1. Biostimulants

Key Highlights

Biostimulants

Seaweed-based biostimulants market: $1 billion in 2022

Global biostimulants market: $2.5–3.5 billion in 2022

Projected market growth: 10 percent CAGR between 2022 and 2030

Projected seaweed-based biostimulants market: $1.8 billion in 2030

Primary drivers

- A growing focus on sustainable farming that supports soil health in a changing climate.
- A significant increase in fertilizer prices.
- Strong integration potential with the production of other seaweed-derived products and existing supply chains due to compatible processing requirements.
- Farmed seaweed offers an opportunity to grow supplies significantly, although currently most supply comes from wild harvesting.

Main challenges

- Low reputation of efficacy of biostimulants in general, resulting from a lack of clear evidence
- Complexity in handling the product requires significant efforts in end-user education.

Outlook: Seaweed-based biostimulants can expect to see significant growth over the next few years as additional investment goes into product R&D for improving efficacy, and as more seaweed processors valorize separate parts of seaweed biomass to create multiple products.

i. Introduction

A growing global population is putting immense pressure on the agricultural sector to produce food in more efficient and effective ways. At the same time, increasingly severe weather events are challenging the productivity of farms around the world.

Biostimulants are agricultural inputs that mitigate abiotic stress and enhance plant productivity through increased biological activity. They can be applied to maintain or increase crop yields and crop quality without increasing – or even reducing – fertilizer use and are therefore increasingly recognized as innovative options for enhancing crop production.

Conventional fertilizers aim to increase the amount of nutrition available in the substrate by direct addition. 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 natural alternatives. There are significant drivers increasing the use of biostimulants – both as a replacement for, and in conjunction with, conventional fertilizers.

Abiotic stress, particularly heat and drought stress, is increasing in critical agricultural markets. Biostimulants offer a low-cost solution to reduce this impact. Biostimulant products are often targeted at the organic agriculture sector because many synthetic crop improvement and defense products do not meet organic standards. Beyond the agriculture sector, biostimulants are also used in horticulture, ornamental plants, and other applications.

ii. Seaweed's value proposition

Seaweed has been used as fertilizers in agriculture since ancient times; fresh seaweed was – and still is – applied directly to fields and gardens (Nabti *et al*. 2017). The use of seaweed-based bioproducts has been gaining momentum in crop production systems in the past 30 years, owing to their unique bioactive components and effects. Seaweeds can be applied as biological agricultural input products in different forms, such as biofertilizers, liming materials, soil improvers, plant biostimulants, and fertilizing product blends.

Most, however, can be classified as biostimulants, since they do not naturally contain a high enough level of fertilizer compounds to qualify as fertilizers but do contain a range of bioactive compounds that stimulate plant growth and development. Nevertheless, there are product blends of seaweed extracts with sufficiently high nitrogen content to classify as biofertilizers. In the US, seaweed-based products can be sold as "seaweed fertilizers" with the addition of just 1 percent conventional fertilizer, which therefore makes it difficult to gauge the actual market size.

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 (Sujeeth *et al*. 2022), owing to the presence of plant growth hormones such as auxins and cytokinins. It has also been reported that seaweed extract can enhance plants' disease-resistance properties (Mukherjee and Patel 2020; Salehi *et al.* 2019). Furthermore, the use of seaweed extracts has been linked to improved water-holding capacity and improved microbial soil communities (Deepika *et al*. 2022; Salehi *et al*. 2019). Consequently, the application of seaweed biostimulants, and the accompanying potential benefits for soil and plants, can enhance production yields (Deepika *et al*. 2022; Salehi *et al*. 2019).

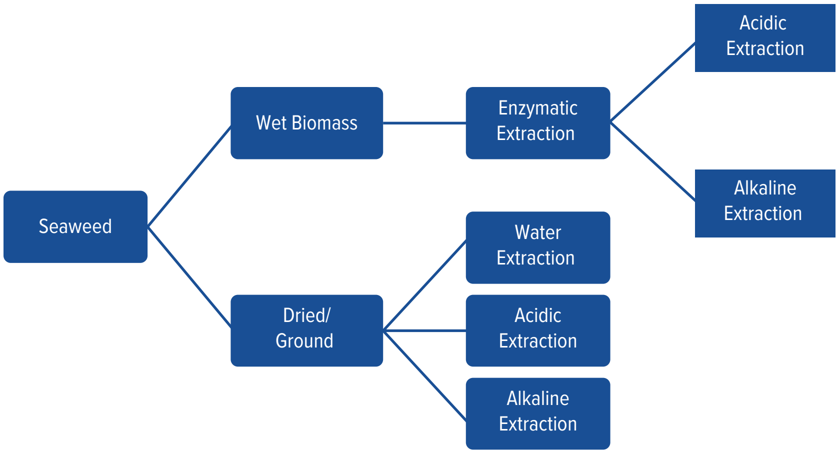
iii. Processing

Currently, seaweed used for biostimulants is mainly wild-harvested, and the main species used are a small number of brown seaweeds, because of the type and concentration of key bioactive compounds – such as laminaria, fucoidan and mannitol – that they contain. Many of the seaweed-based biostimulant-producing companies use *Ascophyllum nodosum* for its impressive performance in reducing the effect of abiotic stress on crops.

Seasonality is an issue because the content of these beneficial compounds can vary between 0–15 percent, depending on the time of year. For other seaweed groups, the bioactivity of the compounds is less well determined.

The main processing step includes liquid extraction and/or drying and grinding. The extraction phase remains the most decisive step for the development of agronomically efficient biostimulant products, as it has a significant impact on economic viability. Seaweed-based biostimulant developers use a range of seaweed compound extraction techniques, including enzyme-assisted, acidic, and alkaline extraction. The seaweed extract makes up approximately 6 percent of the wet biomass in a liquid extraction process. For biostimulants, alkaline extraction with potassium hydroxide is the most common current method, accounting for around 80 percent of all biostimulants. However, companies such as Algaia in France extract their biostimulants in water in an effort to reduce the use of heat in the process, thereby preserving bioactivity levels. Biostimulant extraction can also be applied as part of carrageenan or alginate processing, and as a secondary product to existing processes.

FIGURE 8: Biostimulant processing flow



The intermediate or final product is then shipped to sales channels and/or is rebranded, by either the biostimulant end-product producer, an end-product repackaging or rebranding entity, or an agri-inputs trader. The products are then sold directly, via B2B channels, wholesalers, and/or retailers to end users including farmers, gardeners, and household consumers.

iv. Market overview

The global market size for biostimulants in 2022 is estimated at somewhere between $2.5 billion and $3.5 billion at the manufacture level, and has a CAGR of around 10 percent.

There are four main segments in the biostimulant market: seaweed extracts, fulvic or humic acids, microbial biostimulants, and amino acids. Of these, seaweed extracts are the largest, accounting for around 40 percent of the total market, with a value of approximately $935 million in 2021. Humic and fulvic acids are the second-largest segment, with a value of around $843 million (S&P Global 2022).

Fulvic and humic acids account for a similar market share and are cheap to produce but are not as effective as the other product categories. Their mode of action is better understood, but their sustainability is in question since they are mined minerals, rather than organic compounds or microorganisms. Microbial extracts, amino acids, and trace elements together account for the final third of the biostimulant market.

TABLE 5: The market share of biostimulant categories, according to interviews and adapted from S&P Global 2022

Category	Market share	Market value 2021
Seaweed extracts	40%	$935 million
Fulvic/humic acids	36%	$843 million
Microbial biostimulants	10%	$233 million
Amino acids	10%	$233 million
Trace minerals and others	4%	$100 million

The major segment, by crop type, of the total global biostimulant market is represented by the biostimulants used for row crops – such as cereals, potatoes, soybean, maize and rice – followed by fruits and vegetables. The two categories together represent 80 percent of the total market. By geography, Europe appears to be the largest market for biostimulants, followed by Asia-Pacific.

The strong growth predicted in the global biostimulant market has led to the entry of two new waves of companies. The first wave are large companies entering the top end of the market, often by acquiring biostimulant technologies or product lines. The second are small research companies. Meanwhile, the sector is still defined by the involvement of many long-standing small- and medium-size enterprises (SMEs). This has been encouraged by the absence of registration requirements in many countries and resulting low entry barriers. It typically takes only 2–5 years to bring a new biostimulant product to market.

More than 500 companies are involved in the biostimulant and biological control agent market, many selling both types of products. These include fertilizer companies, agribusinesses, and specialist biological companies. The market is highly competitive, with relatively low barriers to entry compared with those for the conventional crop protection market. Many biostimulant manufacturers are comparatively small companies that do not have the resources or infrastructure to distribute products themselves. Two business models are especially common in the seaweed-based biostimulant market: In the B2B business model, companies source seaweed biomass, extract biostimulants, and sell to large, international agrochemical or fertilizer companies using a distribution or retail network that sells other crop inputs, along with third-party labeling.

In the second model, B2B2C, companies develop their own branded products, based on specific formulations with particular attributes, and sell through established market channels. Since the company takes on the market risk in this model, it is less common than B2B channels, and relies on high-value customers, such as horticulturalists.

In terms of quality, companies such as Acadian Seaplants, BioAtlantis and Maxicrop are among the leading providers of seaweed-based biostimulants; in terms of volume, Chinese companies are leading. Most of the products in this category are liquid, which implicitly means that they are mainly applied via foliar spray or irrigation water. It is difficult to determine which seaweed species are specifically used per industry category. Most of the seaweed-based biostimulants consist of a mix of seaweed and other active ingredients, and these mixes differ in each product.

Prices are typically set by the producers together with the distributors according to market demand; consequently, they can vary significantly between countries and regions. In North America, most algae extracts sold as biostimulants range between $8 and $20 per liter. In Europe, products based on wild-harvested *A. nodosum* range between 5 to 16 EUR per liter, while the recommended retail price for *Ecklonia*-based products is around 20 EUR per liter.

v. Market dynamics

Drivers

From an environmental perspective the main drivers of the biostimulant market are the growing pressure on conventional horticultural and agriculture systems because of climate change, land scarcity, and decreasing biodiversity.

At the same time, increasing consumer demand for organic foods and the implementation of organic regulations and other policies are driving the growth of biostimulants. More government subsidies, financial aid, and research assistance from regulatory bodies and organizations are being devoted to producing a range of crops organically. This has fueled growth in the biostimulant market in terms of value. However, compared with the global agricultural industry, it is still a very small market.

Although biostimulant products have been around for many years, sales began to take off two decades ago. The reasons for this include the growing population; the development of more effective products; the possibility of filing patents to protect innovations; the entrance of new investors; better knowledge among growers; and the development of legislation to boost grower confidence.

A new factor influencing biostimulant demand is the rise of global fertilizer prices because of the war in Ukraine and an increase in energy prices. Industry experts suggest that this price increase – by 30 percent on average in 2022, and by up to 80 percent in 2021 (Baffes 2022) – is pushing the market toward alternative products. Because of their sustainable production process, seaweed-based biostimulants are, and will remain, of interest to the market. It is also predicted that microorganism-based biostimulants will increase market share over the next decade, while other biostimulant categories have lower growth forecasts.

Challenges

Factors impacting the market include the poor reputation of biostimulants and, for some products, the lack of convincing evidence of their efficacy. The difficulty of extracting the bioactive compounds, and the complexity of their mechanism of interaction with soils, have together created inconsistent performance and, over time, a reduced level of trust in the effectiveness of these products.

As the sector is comparatively new, for many end-users, and even for some providers of biostimulants, it is not always clear what the exact efficacy of biostimulants is. Furthermore, customers are not always properly informed about the proper way to use them (dosage, application rate, when to apply, and so on). Biostimulants in general are complex products with many components, each with a specific effect. As a result, they often require more targeted applications to retain optimum bioactivity. This may increase the complexity of handling biostimulant products and lead to variations in performance, despite controlling other variables. The wide variability and variety of chemical compounds available in a seaweed extract makes it more difficult to pin down which bioactive compound, or combination of compounds, is creating the desired effect.

Examples of studies of mode of action of seaweed-based biostimulants and their effects are summarized by Sujeeth *et al*. (2022). What most studies show is that it is difficult to be exact about causation with complex products working in complex environments. Each individual field can often have its own unique soil characteristics, which can have an effect on the efficacy of the biostimulant on the crops. Biostimulant producers explained that, in the near term, it is likely that the use of biostimulants will increase a farmer's cost of fertilization per hectare. It will therefore require proven efficacy and evidence of increased yields to justify the increased cost. Fluctuating commodity prices mean that, when the prices of conventional fertilizers are low, growers may be less keen to invest in biostimulants.

Aside from the challenges of understanding the mode of action, proving efficacy, and optimizing application, it is a risk to adopt an expensive new product. Financial support would enable or accelerate the adoption of biostimulants. There are a range of options – from government subsidies, to increasing end-product prices through organic labeling, to connecting the increased ecosystem services derived from biostimulant use to a system of ecosystem service payments for carbon sequestration, nitrogen runoff mitigation, or increases in biodiversity.

Biostimulant producers also argue that better insights are required into the market's demands. A lack of knowledge of these demands can be interpreted in several ways: either the market is not easily accessible and transparent, or biostimulant producers do not conduct enough in-depth market research themselves. Furthermore, there has been significant uncertainty in the marketplace in recent times, with companies making contrasting claims regarding the mode of action and the constituents of seaweed extracts (Sujeeth *et al*. 2022).

From a startup perspective, working with already established incumbents who control the distribution networks creates a product development challenge. To integrate into fertilizer product portfolios requires a significant, proven, competitive advantage over existing products. Where a product is unproven, working with a large agricultural corporation on field trials is often the only option and creates a barrier to entry for biostimulant developers. Companies producing biostimulants have often been too small to fund such research.

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. Interviewees highlighted that much progress has been made in crop monitoring and agronomic sophistication, but the fastest way to proving 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.

Regulation

The rapid growth in the market for biostimulants has outpaced the development of legislation to regulate this sector. Each country has its own legislation about biostimulants, covering the requirements with which a biostimulant product must comply before it may enter the market. These requirements are based on the definition of the biostimulant, which also determines in which legislative category (fertilizer or protection agent) the biostimulant can be registered, and this differs in each country. On an international level, there is still a lack of standards, which makes it difficult to bring new biostimulant products to the market. There is a need for uniform global legislation on biostimulants.

The International Organization for Standardization (ISO) has started work to create a standard on biostimulant terminology. In the meantime, the biostimulant standards from the EU and US are summarized below:

The new EU Fertilizing Products Regulation (EU) 2019/1009 came into force in July 2022. The regulation is a milestone on the path toward the market adoption of biostimulants, by regulating a biostimulant product as opposed to a fertilizer or a plant protection product. The regulation's definition of a plant biostimulant is a product that stimulates the nutritional processes of plants independently of the nutrients it contains, with the sole aim of improving one or more of the following characteristics of plants or their rhizosphere:

1. The efficiency of nutrient use
2. Tolerance to abiotic stress
3. Qualitative characteristics
4. The availability of nutrients confined in the soil or rhizosphere

The United States is the only other jurisdiction where biostimulants are defined and regulated. The 2018 Farm Bill stipulated that a biostimulant is a substance or microorganism that, when applied to seeds, plants, or the rhizosphere, stimulates natural processes to enhance or benefit one of the following:

1. Nutrient uptake
2. Nutrient efficiency
3. Tolerance to abiotic stress
4. Crop quality
5. Yield

Simultaneously, regulation, particularly in Europe and the US, but also in an increasing number of other countries, is forcing farmers to seek alternatives to synthetic chemical inputs. The EU's Farm to Fork strategy sets concrete targets to transform the region's food system – including reducing the use of pesticides by 50 percent, and for 25 percent of its agricultural land to be farmed organically.

However, despite efforts from regulators to increase the ease and speed of regulatory approval of biostimulants through clearer legislation, even in the most pioneering regulatory frameworks there is some concern that biostimulant regulation may increase the farmers' ability to use conventional fertilizers through poorly regulated blended biostimulant and fertilizer products.

vi. Market outlook

There clearly is momentum pushing agricultural systems to adopt alternatives to synthetic fertilizers, with biostimulants being a leading solution. The global biostimulant market is projected to grow at a compound annual growth rate (CAGR) of approximately 10 percent per year. A significant proportion of market growth is expected to be driven by regulatory pressure to find alternatives to synthetic fertilizers.

The global seaweed-based biostimulants industry is already valued at $1 billion and, it is projected, will reach $1.8 billion by 2030, maintaining, if not increasing its 30 percent market share of the biostimulants market.

The outlook for seaweed's market share is positive. Biostimulants are an attractive market for developers of seaweed-based products and there is interest in investing further, for the following reasons:

- They are relatively simple to produce – most products are mechanically extracted liquid fertilizers.
- The solid co-product from this process can be sold as animal feed or pet food, while the biostimulant can be a co-product to hydrocolloid processing.

- The market has low regulatory requirements.
- The route-to-market is relatively fast and simple. There are established supply chains in place for agricultural inputs, and large global operators are looking for new products for their portfolios and sales channels.

The challenges for this market will center on proving efficacy, scaling supply, and integrating seaweed-based biostimulants into existing supply chains.

Increased understanding of seaweed-based biostimulants' modes of action should also increase regulators' abilities to create standards and clearer regulatory definitions. One interviewee expects it will take five years until a higher level of standardization is achieved. In Europe, the Bio4Safe.eu initiative has recently released an open-source database in which customers can search available biostimulant products, based on the desired effect and crop group. This points to a key knowledge gap in this industry.

Based on the interviews, an increasing trend toward blending biostimulants with conventional macronutrient fertilizers is expected. Secondly, interviewees expect further research into the mode of action of specific bioactive biostimulant compounds in field trials, in order to discover the most effective compounds, the most effective way to apply them to various crops, and at what point of the growth cycle. It will also have to be determined whether bioactive compounds can be applied in a more targeted manner, as this will be essential in developing a strategy for how the seaweed-based biostimulant sector could be developed.

Although Europe currently accounts for the largest market share, strong growth in the Asia-Pacific region is expected. Increased food demand, particularly in China and India, coupled with a growing focus on sustainable farming and enhanced productivity, will fuel the consumption of biostimulants in the region. This creates a unique opportunity to produce more biostimulants from the seaweed cultivated in these Asian regions. With the current estimated growth of the biostimulant sector, it will be essential to work toward an increased level of resilience in the local supply chains of seaweed that can be used for the development of seaweed-based biostimulants. A resilient supply chain could include a combination of both wild-harvested and cultivated seaweeds.

A diversification of seaweed species used for biostimulants could strengthen the supply chain in case of the emergence of pests, diseases, or other crises. Equally, breeding technologies could help improve the composition of those seaweeds that are grown specifically for the biostimulant market.

4.2. Animal feed additives

Key highlights

Animal feed additives

Seaweed is already used in the animal feed industry as a feed additive and feed ingredient, but no data on market size are available.

Global feed additive market: $38.86 billion in 2022.

Projected market growth: 3.9 percent CAGR between 2022 and 2030.

Projected seaweed-based animal feed additive market: $1.122 billion in 2030.

Key drivers

- Increasing public concerns about the quality and safety of meat, and outbreaks of livestock diseases.
- Productivity gains and the potential to improve feed conversion ratios are economic incentives for farmers.
- Unique functional benefits of seaweed-based products that can help reduce the application of animal antibiotics.
- Costs of seaweed-based products are already competitive with other feed additives.

Main challenges

- Availability of sufficient volumes of seaweed.
- Customer onboarding and demonstrating results through large-scale trials.

Outlook: Seaweed-derived feed additives are expected to outpace other applications over the next five years. There are powerful drivers at work as customers turn to natural alternatives to synthetic products. Improvements in feed conversion ratios are especially promising.

i. Introduction

Global population growth, projected to reach 9 billion by 2050, has raised concerns about the ability to produce enough food to meet demand. One key challenge is the continued and increasing demand for animal-based protein, which depends on a reliable, cost-effective supply of animal feed.

Currently, the two main feedstocks used as the primary sources of nutritional energy and protein for animal feed are soybeans and maize. But these products are also used in human food. Consequently, animal feeds that compete less with human food pathways have been growing in popularity. Finding ways to sustainably and efficiently produce these feeds will be crucial in ensuring the long-term sustainability and viability of food production systems.

BOX 2: ANIMAL FEED MARKET DEFINITIONS

Feed materials: These have been defined by the EU as feed components that are principally purposed to meet animals' nutritional needs

> in their natural state, fresh or preserved and products derived from the industrial processing thereof and organic or inorganic substances, whether or not containing feed additives, which are intended for use in oral animal-feeding either directly as such or after processing or in the preparation of compound feed or as carrier of premixtures. (FEFAC 2018)

Feed additives: the EU defines additives for use in animal nutrition as

> substances, microorganisms or preparations, other than feed material and premixtures, which are intentionally added to feed or water in order to perform, in particular, one or more of the following functions: (1) favourably affect the characteristics of feed, (2) favourably affect the characteristics of animal products, (3) favourably affect the colour of ornamental fish and birds, (4) satisfy the nutritional needs of animals, (5) favourably affect the environmental consequences of animal production, (6) favourably affect animal production, performance or welfare, particularly by affecting the gastrointestinal flora or digestibility of foodstuffs or (7) have a coccidiostatic or histomonostatic effect. (EUR-Lex 2018)

(Box Continued)

BOX 2: *Continued*

Alternatively, the organization FEFANA classifies feed additives as **specialty feed ingredients (FEFANA 2023)**. This means they provide micronutrition, technological, sensory, or zootechnical functions. Feeds that incorporate these specialty ingredients can be called "**functional feeds**" as they promote the growth and immune systems of animals beyond traditional feeds (Alemayehu *et al*. 2018).

Feed supplements: can be defined as a combination of nutrients added to feed to improve the nutrient balance or performance of the total ration. They are intended to be (1) diluted with other feeds when fed to livestock, (2) offered free choice with other parts of the ration if separately available, and (3) further diluted and mixed to produce a complete feed.

ii. Seaweed's value proposition

One solution to this problem is seaweed, which has been eaten by domesticated animals for centuries (Balasse *et al.* 2019). Its suitability as an alternative feed component stems from its balanced amino acid profile, rich mineral and vitamin content, and special combination of bioactive compounds. These can improve nutrient absorption and provide a range of performance benefits for multiple species of animals. For example, polysaccharides contained in some species of seaweed have a prebiotic effect in the microbiome of animals.

Table 6 shows an assortment of animal tests performed *in vivo*, using different seaweed species, showcasing the positive effects of using macroalgae in animal feeds. It also highlights a selection of commercial products currently available on the market from farmed and wild-harvested seaweed.

TABLE 6: Sample of seaweed studies and products highlighting effects on animals.

Sample of seaweed studies			
Study	**Type of seaweed**	**Animal species**	**Noted effect in animals**
Chaves Lopez *et al.* 2016	Brown - Ascophyllum nodosum	Cattle	"Led to an increase in iodine content in milk and to a modification of cow microbiota, with a positive effect on milk hygiene and transformation."
Rey-Crespo *et al*. 2014	Green - Ulva rigida	Cattle	"Improved animals' mineral status, particularly iodine and selenium, that were low on the farm."
Roque *et al*. 2019	Red - Asparagopsis armata	Cattle	"Methane production by cows decreased significantly. Total feed intake was reduced. Bromoform concentrations in milk were not significantly different between treatments."
Moroney *et al*. 2015	Brown - Laminaria digitata	Swine	"Results indicated that adding laminarin and fucoidan extracts in pig diets for 3 weeks enhanced pork quality."

(Table Continued)

TABLE 6: ***Continued***

Sample of seaweed studies			
Study	**Type of seaweed**	**Animal species**	**Noted effect in animals**
Bussy *et al*. 2019	Green - Ulva armoricana	Swine	"Supports the use of natural algae extract (MSP) as an immunomodulating solution in swine production."
Carrillo *et al*. 2012	Brown - Sargassum sinicola	Poultry	"Had some beneficial effects on n-3 fatty acid content found in eggs."
Li *et al*. 2019	Green - Ulva	Poultry	"Can significantly improve egg production, increase egg weight, and decrease feed conversion ratio. Also helped to improve the eggshell strength, leads to a yolk colour with red tendency, and can significantly decrease cholesterol levels of yolk."
Marinho *et al*. 2013	Green - Ulva	Finfish	"Incorporation of IMTA-produced Ulva meal into Nile tilapia diets is possible up to 10% without compromising growth performance, protein utilization, or protein retention of juveniles. The high capacity of Nile tilapia to digest all experimental diets suggests that Ulva meal is a practical partial replacement for fish meal in Nile tilapia diets."
O'Mahoney *et al*. 2014	Brown – Laminaria digitata	Abalone	"This study highlights the potential for a mixed species seaweed meal as a fish meal replacement in formulated feeds for abalone."

Sample of commercial products			
Commercial producer/ product	**Type of seaweed**	**Animal species**	**Intended effect on animals**
Ocean Harvest Technology/OceanFeed Bovine	Mixture of green, brown and red seaweeds	Cattle	Improved nutrition and milk yields
Ocean Harvest Technology/OceanFeed Swine	Mixture of green, brown and red seaweeds	Swine	Improved feed conversion, digestive balance, piglet viability, reduced diarrhoea
Tasco/Acadian	*Ascophyllum nodosum (B)*	Horses	Prebiotic, supports immune health, enhanced resistance to environmental stress (e.g. transport, heat), promotion of a healthy skin and shiny coat
		Cattle	Coping with heat stress, support immune system, milk production, reproduction functions
Celtic Sea Minerals/ CeltiCal	*Lithothamnium calcareum®*	Swine	Healthy gut and digestive function, improvement of feed conversion ratio, higher piglet birth weights, better survival rate for large litter size

Because of its historical use in this context, seaweed is already incorporated into animal feed regulations worldwide. In the EU, it falls under both the “feed materials” and “feed additives” categories.

The principal purpose of a feed material is to meet the animal’s nutritional needs (Bremmers 2016). Seaweed feed materials include “algae-live or processed, regardless of their presentation, including fresh, chilled or frozen,” “dried algae-product” that “may have been washed to reduce the iodine content,” “algae meal – product of algae oil manufacture, obtained by extraction of algae,” “algal oil – product of the oil manufacture from algae obtained by extraction,” “algae extract – watery or alcoholic extract of algae that principally contains carbohydrates,” and “seaweed meal – product obtained by drying and crushing macroalgae, in particular brown seaweed” that “may have been washed to reduce the iodine content” (Michalak and Mahrose 2020).

Meanwhile, seaweed feed additives perform one or more specific micronutritional, technological, sensory, or zootechnical functions and typically undergo additional purification and standardization steps for the claimed active substance (Bremmers 2016). These are also incorporated in animal feeds at low inclusion ratios (typically less than 1 percent). In the EU feed legislation, “extracts” of seaweeds are recognized as “feed additives” (Michalak and Mahrose 2020). In the EU these additives are subject to much more stringent regulations than are feed materials and undergo more tests. Examples of registered seaweed feed additives already on the market can be found in the EU Register of Feed Additives (European Union 2022).

Terrestrial animal feed

Based on the available literature and the interviews conducted for this report, seaweed – either extracts or meals – is mostly sold as supplements for terrestrial animals and are generally incorporated at low inclusion rates – usually lower than 80g/kg feed (Kim 2011; Cruz-Suarez *et al*. 2009). This partly stems from research showing that the use of macroalgae at high inclusion levels proved either inconclusive or harmful to terrestrial animals.

Generally, macroalgae are used as sources of bioactive substances and minerals in livestock feeds, and to a lesser extent, as sources of protein. In terms of composition, the protein and essential amino acid content of macroalgae can vary greatly, and the digestibility of the protein may be affected by certain compounds in the seaweed. This makes it difficult to generalize about the use of whole macroalgae as a protein source, and many species have too little digestible protein to be a viable alternative protein source in animal feed. To overcome this issue, researchers are improving extraction methods to increase the protein content of macroalgae, and biorefinery technologies can establish cost-effective and environmentally friendly methods for extracting bioactive chemicals – such as laminarin, fucoidan, and phlorotannins – which can provide certain health benefits.

The most prevalent algae feed ingredients are derived from brown macroalgae extracts, such as *A. nodosum* for ruminants, at up to 2 percent total feed dry weight, and *Laminaria* sp.-derived polysaccharides (fucoidan and laminarin) for pigs, at up to 0.04 percent feed inclusion rate. Meanwhile, the principal algal feed components for poultry are green seaweeds, such as *Ulva* spp., with a suggested level of up to 10 percent feed inclusion. All of these seaweeds can enhance cattle growth performance and meat quality because of the high nutritional value of algae and the immunomodulatory, prebiotic, and antioxidant characteristics of algal bioactive polysaccharides (Costa *et al*. 2021).

In addition, there are particularly promising results for seaweed-derived swine feed supplements. The benefits of using these supplements include reduced piglet mortality and improved feed conversion ratios, animal health, and sow productivity. There have been positive results from adding fermented seaweed to pig feeds. The company Ocean Rainforest reported in 2021 that up to 80 percent of its annual 250-ton seaweed output would be fermented and sold as pig feed. Results from their trials indicate that fermented seaweed, which makes up 2–5 percent of the pigs' diets, can "reduce the feed consumption of the sows, their antibodies go up by 30–40 percent and it has a direct impact on piglet health, reducing mortalities by 3–4 percent. It means they need less feed and fewer antibiotics, that they produce more piglets and the farmers' profits increase"(Fletcher 2021a).

Aquafeed

Fishmeal has traditionally been the primary protein source in aquatic feed. However, because of overfishing and the increasing demand for natural ingredients, in many feeds alternative plant-based proteins such as soy are being used as a partial replacement. Unfortunately, these plant-based alternatives sometimes lack certain essential amino acids, including lysine and methionine. Although it is possible to substitute individual amino acids in the formation of feed, these amino acids are naturally found in macroalgae. Consequently, seaweeds have been explored in this context for aquatic feed products as a source of proteins, often in formulations tailored to the specific type of fish and its environment.

These seaweed formulations also aim to improve final product texture and flavor, increase yields and reduce the use of synthetic and chemical additives. Macroalgae can provide fish with a number of beneficial organic compounds, like the valuable fatty acids docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), and a range of bioactive polysaccharides that are essential for fish health. Multiple studies have shown the effectiveness of using macroalgae in finfish feeds to enhance their growth rate and immune system (Wan *et al*. 2018). For example, seaweeds such as *Ulva lactuca, Gracilaria* sp. and *Ulva rigida* have been highlighted as suitable additives to enhance the development of European seabass (Wassef *et al.* 2013).

In addition, around 20–30 percent of farmed brown kelps and *Gracilaria* are used as fresh feed for the aquaculture industry in China and South Korea – mainly for abalone, but also for sea cucumber and sea urchins. These seaweeds can be minimally processed. Seaweed can also be fed to shrimp. It forms part of the natural diet of shrimp, which can digest the fiber in seaweed better than the fiber in terrestrial plants. Companies such as Gold Coin have also seen some improvements in palatability performance using seaweed, and there are studies showcasing the potential health benefits seaweed can have when as a feed component for shrimp (Fletcher 2021b; Schleder *et al*. 2020).

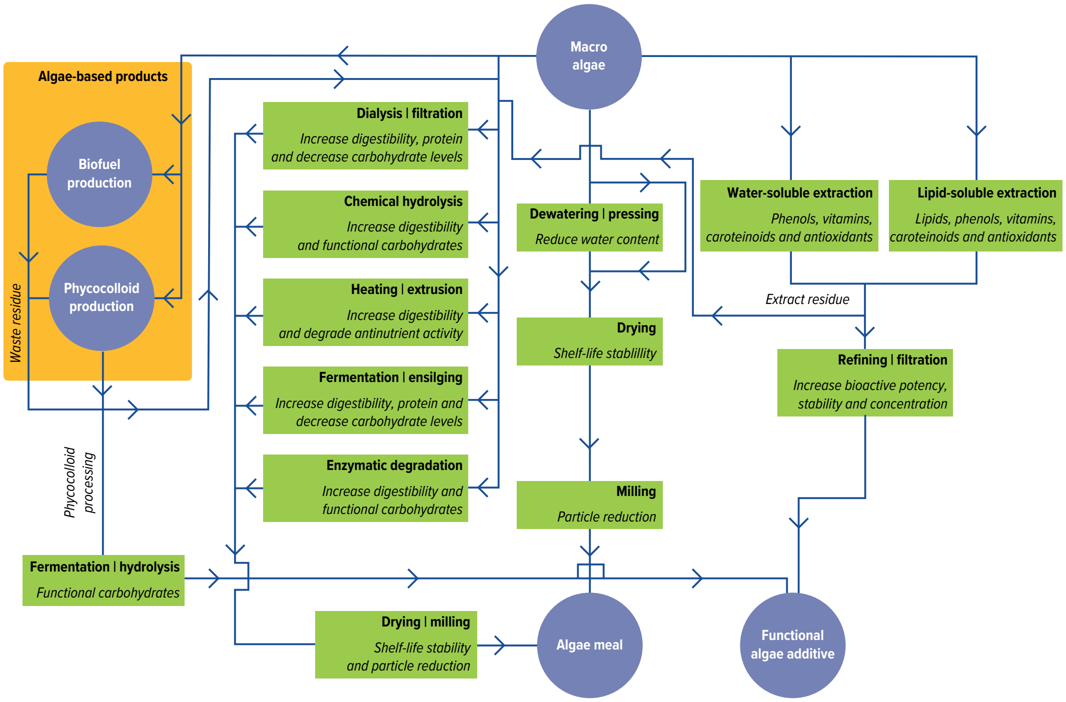
iii. Processing

Both intact and processed seaweeds can be used as a component of animal feeds. Processing can be as simple as drying and milling the seaweed, or may require more steps for enhancing or retaining certain components, improving digestibility, or removing hazardous compounds and antinutritional factors.

Fermentation of seaweed involves using microorganisms, like lactic acid bacteria for example, to make it more digestible, enhance the bioactive profile and help make the product storage-stable. It is commonly used by seaweed animal feed producers and the fermented feed product can be supplied as fermented liquid feed or as a dried product (Stévant and Rebours 2021).

The conversion ratio between wet seaweed and final feed product depends on the level of processing, the seaweed species, and the season. Hebridean Seaweed Company explains that harvesting 40 tons of fresh *Ascophylum nodosum* per day equates to around 10 tons of processed seaweed – ratio of about four to one (McCullough 2019). Processing in this case involves drying wet seaweed and milling. One interviewee stated that with the processing of seaweed, which is done to amplify specific extracts, one can expect 2–7.5 percent conversion from wet seaweed to

FIGURE 9: Potential routes to feed production, as suggested by Wan *et al*. 2018



final seaweed extract. Another set of interviewees suggested a 6.66 percent conversion from wet seaweed to final fermented seaweed additive. To account for this variation in conversion ratios, we assume 1 ton of fresh seaweed yields about 7.5kg of seaweed animal feed additive.

iv. Market overview

According to the 2022 Alltech global feed study, annual worldwide animal feed output increased by 2.3 percent in 2021, with 1.236 billion tons produced (Alltech 2021). Globally, this amounted to a commercial feed manufacturing annual turnover of over $400 billion (IFIF 2021) Asia remained the world's largest producer, with 458 million tons, followed by Europe (267 million tons) and North America (253 million tons).

The market for animal feed additives, by contrast, was valued at $37.4 billion in 2021, and $38.86 billion in 2022, and is expected to continue growing at a CAGR of 3.9 percent from 2022 to 2030, reaching a projected size of $52.77 billion by 2030 (Straits Research 2021a). The animal feed additives market (Yıldız 2021) can be segmented broadly into:

Technological additives: Preservatives and emulsifiers that allow feeds to be stored for a long time without spoiling by improving or stabilizing the physical structure of the feed during production. They usually have no direct biological effect on animal production.

Nutritional additives: Supplements that increase the nutritional value of the feed and, accordingly, the health or athletic performance of animals. They include vitamins, pro-vitamins, and chemically well-defined substances that have a similar effect as vitamins; compounds of trace elements; amino acids, their salts and analogues; urea and its derivatives.

Zootechnical additives: Additives that can improve the performance, physiological functions and wellbeing of animals in good health, or have a positive influence on the environment. They include natural growth-enhancing feed additives, which are generally used instead of antibiotics.

Coccidiostats and histomonostats: Substances used to protect chickens from coccidiosis – bloody diarrhea caused by *Eimeria*-type protozoa that settle in their intestines – by killing the protozoa (bacteria/microorganisms) or preventing their reproduction. They were banned by the EU in 2009 and replaced with probiotic alternatives but are still used in some countries.

Prebiotic additives such as seaweed can fall in the zootechnical additives category. One report indicated that the global zootechnical feed additive market was worth $9.7 billion in 2022. In terms of ingredient type, probiotics lead, with a 52.6 percent market share in 2022. Europe is the largest market, worth $2.8 billion (Fact.MR 2022). Prominent zootechnical feed additive manufacturers include Alltech, Cargill, Delcon, DSM, DuPont, Kemin Industries, and Novus International.

TABLE 7: Prices of ingredients (bulk ingredients and additives) used in animal feeds

Ingredient	Use	Price	Source
Fish meal	Bulk ingredient	$1.495 per kg (average price 2018–2022)	www.indexmundi.com/
Soybean meal	Bulk ingredient	$0.436 per kg (average price 2018–2022)	www.indexmundi.com/
Lysine	Nutritional additive	$1.20–2.80 per kg (between Mar 2022 and Feb 2023)	www.allaboutfeed.net
Theorine	Nutritional additive	$1.28–3.48 per kg (between Mar 2022 and Feb 2023)	www.allaboutfeed.net
Vitamin A	Nutritional additive	$24.5–76 per kg (between Mar 2022 and Feb 2023)	www.allaboutfeed.net
Vitamin D3	Nutritional additive	$7.9–16.9 per kg (between Mar 2022 and Feb 2023)	www.allaboutfeed.net

v. Market dynamics

Drivers

There are several drivers of the animal feed and animal feed additive markets. For example, rising disposable income and a growing global desire for meat has been increasing the demand for animal protein.

Second, the public's growing knowledge about meat quality and safety, outbreaks of livestock illnesses, and the potential in improving feed conversion ratios are driving an interest in seaweed as a functional feed additive (Allied Market Research 2021). Several studies and products outlined in Table 6 show the beneficial effects that seaweed feed additives can have on animal health. For example, adding seaweed to piglet feed has been shown to be a cost-effective way to reduce mortality rates caused by disruptions in the digestive system after weaning.

Third, regulatory pressure on animal feed in several regions is another driver. For example, in June 2022, Europe banned the direct use of medical zinc oxide –previously used as a prophylactic – in feed. Seaweed feed additives present an attractive alternative (Hui *et al*. 2021). In addition, they can help reduce the application of animal antibiotics. This could help countries like Vietnam, where extensive and unregulated use of antibiotics has caused antibiotic resistance. Several countries have now prohibited the use of antibiotics as growth promoters in animals and, in 2023, the EU introduced a ban on the routine use of antibiotics in livestock farming (World Animal Protection 2022). According to the interviewees consulted for this report, this is driving the implementation of natural alternatives such as seaweed supplements.

Additionally, livestock owners are attracted to the environmental benefits of using seaweed in animal feed, including the opportunity to participate in voluntary carbon certification schemes, as offered by The Seaweed Company and Ocean Harvest Technology, who cultivate seaweed for animal feed products. There is also a general impetus to find alternatives to common feed components such as maize and soy, and using seaweed could alleviate increasing competition between the food and feed chains (Costa *et al*. 2021). Over the last few decades, several large companies – including Alltech, Ocean Harvest Technology and Acadian Seaplants – have been building on these drivers and producing seaweed-based commercial feed products for farm and aquatic animals (Adarme-Vega *et al*. 2012).

In the case of aquafeed, a significant portion of the costs of fish and shrimp aquaculture are associated with commercially prepared feed, and growing demand combined with the stagnation in the production of fishmeal and fish oil has led to a rise in feed prices. Feed often accounts for more than 50 percent of farm production costs (BIM 2020). As a result, research organizations and feed producers are seeking new, environmentally friendly and economically viable sources of feed ingredients to replace fishmeal and fish oil. As global wild fish stocks and arable land come under increasing pressure, seaweeds may offer a viable and sustainable alternative to traditional aquafeed ingredients. The bioactive compounds in them have been shown to benefit farmed finfish in past studies. These functional compounds could be of interest to feed manufacturers and fish farmers looking for additional benefits beyond basic nutrition (Wan *et al*. 2018).

Livestock

Companies in the seaweed-based animal feed industry have been growing consistently in recent years. For sustained growth in this sector, access to a large volume of biomass is crucial. Leading companies in this industry are able to achieve this by processing and manufacturing products in high-volume producing nations, such as Vietnam and Indonesia, where seaweed can be found at a farm-gate price of $500–$1,200/ton dry weight (Rimmer *et al.* 2021). Ultimately, this is a high-volume, low-margin business, with dried seaweed supplements selling mostly between $350 and $10,000/ton depending on the functional benefits of the feed, the species, and whether the seaweed was cultivated or wild-harvested (Nieuwenhuizen, C, 2019). To create an economically feasible product in the short term, companies may need to vertically integrate to ensure that the price of biomass is low. Importantly, seaweed supplements with proven health benefits can fetch premium prices and capture a portion of the feed additive market.

According to the interviewees, larger buyers and product developers in this category are known to require upward of 2,000 tons of cultivated seaweed (for example, *Saccharina latissima* or *Alaria esculenta*) wet weight per year for animal supplement products. In Norway, the values of cultivated *S. latissima* in 2018 and *A. esculenta* in 2016/17 were $488 and $3,367–$4,127 per wet ton, respectively (BIM 2020). In 2022 less than 550 tons of cultivated *S. latissima* was harvested in Norway (Forbord 2022). The hope is that, with economies of scale, these prices will decrease significantly to ensure commercial viability.

Alternatively, companies use wild-harvested seaweed. In Norway, seaweed meal, used as an animal feed additive, has been manufactured since the 1960s. It is manufactured from wild-harvested, dried, and milled brown seaweed. As early as 2003, a yearly harvest of around 50,000 tons of wet seaweed yielded 10,000 tons of seaweed meal and sold for $5 million, or $500/ton (FAO 2003). The industry in Norway is largely based on the supply of material for alginate extraction. Around 150,000 wet tons of *Laminaria hyperborea* are harvested each year, largely from the wild. The average price is $25/ton wet weight, and about 5,000 tons of alginate are produced.

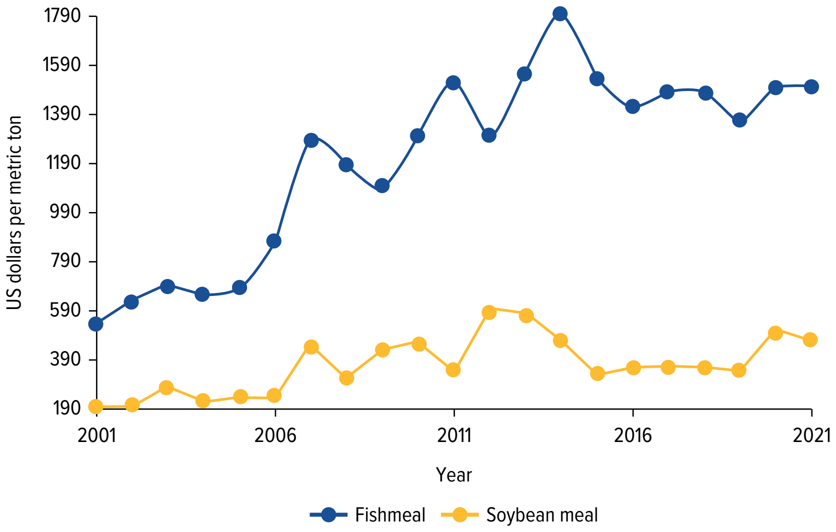
Around 10,000–20,000 wet tons of *A. nodosum* are also wild-harvested per year, mostly for use in seaweed meal, agricultural, nutraceutical and cosmetic products. Wild-harvested *A. nodosum* typically sells for approximately $54/wet ton (BIM 2020).

Selling seaweed as a bulk protein feed for livestock is not currently economically viable, as it would need to compete with soy-derived products (soybean meal, concentrate and isolate) which are priced below $1,000 per ton. Consequently, teams are implementing seaweed as a supplement with significant impacts on the immune system, not as a protein substitute. Interviewees highlighted how small volumes of seaweed can result in significant improvements in immune function, leading to more favorable feed conversion ratios (FCRs) and reduced energy expenditure. According to The Seaweed Company, their animal feed blends have been shown to improve FCRs by 3–10 percent, which reduces farmers' overall carbon footprint. For example, a 10 percent improvement in FCR for 100,000 pigs can lead to a reduction of 18,000 tons of CO_2e per year (Yıldız *et al*. 2021).

Aquafeed

Stagnation in the production of fishmeal and fish oil has led to an overall increase in fish feed prices, as can be seen in Figure 10. In response, feed producers are searching for economically viable sources of ingredients. These alternatives must maintain the growth, health, survival, and fillet quality of farmed fish. Soybean meal and soybean extracts are alternative protein sources, and price points are certainly more favorable (about $0.3–$2/kg, depending on processing level and protein concentration). Seaweed protein extract has also been explored in fish feed but is currently not cost-competitive with soybean meal or soybean concentrate. Despite this, some recent studies have highlighted how creating functional aquafeeds that incorporate highly valuable laminarin and mannitol extracts from seaweed increases the chance of commercial profitability (Emblemsvåg *et al*. 2020).

FIGURE 10: Price comparison of soybean meal and fishmeal



Source: Nagappan *et al*. (2021)

Competition

From a protein perspective, seaweed is unlikely to reach competitive price points. Over the past few decades, several new seaweed-based feed proteins have been developed but few have gained significant market penetration. To replace current feed proteins, like soy and maize, new proteins must have equivalent or superior nutritional values as well as financial and/or functional benefits. They must also have a more favorable environmental impact than soy and fishmeal, as well as other methods used to treat unused raw materials that may be used as inputs or feedstocks.

According to the stakeholder interviews undertaken for this report, based on the relatively low protein content found in seaweeds (see Table 11), alternative protein sources such as yeast, bacteria, insects, and even microalgae are preferred for the production of alternative animal feed proteins. For example, many wild animals, including freshwater fish and birds, consume insects as part of their diet. Insects can contain 56–82 percent protein after de-fatting, making them a potentially intriguing source of protein for animal feed (Gupta *et al*. 2021). However, high production costs also limit the scaleup of insect proteins for animal feeds.

TABLE 8: Prices [$/kg] of several alternative proteins

Type of protein	Price [$/kg] – 100% protein
Soy protein	2.0
Pea protein	5.0
Insect protein	41.0
Mycoprotein	13.0
Cultured meat	300.0
Whey protein	7.5

Source: McKinsey Report (2019)

TABLE 9: Typical composition of commercially available feed ingredients and algae species (dry matter)

	% Crude Protein	% Crude Lipid	% Crude Carbohydrate*	% Ash	Gross Energy MJ/kg
Fish meal	63.0	11.0	-	15.8	20.1
Poultry meal	58.0	11.3	-	18.9	19.1
Com-gluten	62.0	5.0	18.5	4.8	21.3
Soybean	44.0	22	39.0	6.1	18.2
Wheat meal	12.2	2.9	69.0	1.6	16.8
Spirulina	58.0	11.6	10.8	13.4	20.1
Chlorella	52.0	7.5	24.3	8.2	19.3
Tetraselmis	27.2	14.0	45.4	11.5	18.0
Gracilaria sp[1]	34.0	1.5	37.1	26.9	13.4
Gracilaria sp[2]	10.0	0.9	50.1	34.0	11.2
Ulva lactuca[1]	37.4	2.8	42.2	17.4	15.7
Ulva lactuca[2]	12.5	1.0	57.0	24.5	11.2
Schizochytrium[3]	12.5	40.2	38.9	8.4	25.6

* Carbohydrates calculated as the difference % DM - (% protein + % lipid + % ash)

[1] Cultured in effluent of fish tanks

[2] Collected from natural habitat

[3] Commercial product, Martek Biosciences

Source: Shields and Lupatsch (2012)

From a functional feed perspective, macroalgae stand out because of their unique blend of properties and antioxidants. They may face competition from more easily engineered organisms like microalgae, which have also been used as feed supplements and offer many ecological benefits. However, the main challenge for microalgae is scalability. Large facilities are required for microalgae production, which are more technically demanding and expensive than those used for macroalgae.

vi. Challenges

1. Availability of seaweed supply

The production and development of seaweed as a feed additive faces several challenges. First, there are difficulties in creating scalable cultivation methods for different types of seaweed (brown, green and red), as well as challenges in seeding substrates, harvesting at larger volumes, and processing high volumes efficiently. Each variety of seaweed requires substantial technical development to extract and analyze the components of interest. For example, feed makers may require a specific proportion of carbohydrates in their products, which may be limited in farmed seaweed species, according to seasonality. In addition, the relatively indigestible carbohydrate content of some seaweeds, such as kelp, is a potential drawback. To manage this, more testing of cultivated seaweeds, especially fermented raw materials, would be beneficial (Stévant and Rebours 2021).

There are also issues in establishing a secure and traceable supply chain. Wild seaweed is harvested either through beachcombing, cutting, or dredging. Dredging techniques, in particular, can be harmful to the environment because the seaweed is pulled from the seabed. The combination of environmental concerns, control over supply, and the fact that less than 3 percent of total seaweed production is from wild harvesting, is driving downstream product developers to explore vertical integration to ensure a stable supply of biomass which can meet demand for products.

In addition, major animal feed customers often require high biomass volumes and have expressed doubts that sufficiently large volumes of product will be continuously available. These aspects can increase the startup costs for new entrants into the market and create significant entry barriers.

2. Nutritional quality of seaweed

The production and processing of macroalgae for use as animal feed may be hampered by the possible bioaccumulation of seawater inorganic elements and heavy metals – such as arsenic, mercury, lead, cadmium and aluminum – in the macroalgae. In addition, the nutritional quality of processed macroalgae may be impaired because of nutrient loss, and the production of macroalgae on a large scale requires significant energy to harvest and dry it. LCAs demonstrate that, if left untreated, these concerns may have substantial environmental implications, such as elevated carbon emissions (Costa *et al*. 2021).

3. Customer onboarding

It can be difficult and time-consuming to assess some of the beneficial effects of seaweed, and it may require testing them on thousands of animals on commercial farms. Providers of blended seaweed ingredients for the animal feed market need to have the research data to demonstrate the mode of action and efficacy of their products, sometimes in multiple animal species. They need to gain credibility with nutritionists and other key decision makers in the sector to encourage the adoption of these ingredients. For some customers, these natural ingredients are a very new concept, especially if they have been using synthetic products for decades. As a result, customers often need time to conduct their own trials and are not likely to make a quick decision to switch.

vii. Regulations

Although regulations vary across geographies, most regions have established guidelines for algae meal and algae extract feeds. For example, EU guidelines specify maximum levels of arsenic, lead, cadmium and mercury in algae feed materials. The maximum level of arsenic in macroalgae feed materials, for instance, is 10 mg/kg for complete and complementary feed for pets, and 40 mg/kg for macroalgae meal and macroalgae-derived feed materials for livestock (Lähteenmäki-Uutela *et al*. 2021). In the United States, the FDA is responsible for regulating animal feed and pet food. To be approved for use as a feed additive, products must be shown to be safe not only for farm animals to consume but also for humans to eat animals that consumed the feed.

viii. Market outlook

Milestones and projections

Wild-caught and cultivated seaweed are both already competitive in the global feed additive market, which was valued at $38.86 billion in 2022 and is predicted to grow at a CAGR of 3.9 percent until 2030. Based on our analysis of key drivers and dynamics, the projected seaweed-based animal feed additive market will be worth $1.122 billion in 2030.

Interviewees suggested that the market is expected to continue growing steadily over the next 10 years and remains promising for seaweed in the short-term. Based on this, several regions have forecast large future markets in this area, with the European seaweed animal feed supplement market potentially reaching a total market value of $2.414 billion by 2030 (Vincent, Stanley, and Ring 2020).

Due to the functional and economic benefits of seaweed, the level of understanding and interest in the ingredient has increased significantly over the past 18 months, with customers expressing more curiosity and wanting to see data on its effectiveness. According to the SeaMark project, FermentationExperts, currently the largest users of seaweed in animal feed in Europe, expect to be able to increase their usage of seaweed by ten times over the next five years (Feed Navigator 2022). In addition, the promising results for seaweed-derived swine feed supplements mentioned in the value proposition section are encouraging more farmers to consider using them. However, there is currently a challenge in meeting the demand because of inadequate seaweed supply.

According to the interviewees, the drive to reduce antibiotic resistance is promoting the implementation of natural alternatives to antibiotics – such as seaweed supplements – and the industry is moving away from synthetic additives. In addition, according to primary interviews, despite pushback from global pharmaceutical players, changing legislation relating to sustainable farming practices in regions like the EU will likely incentivize adoption regardless. Numerous sustainability advantages are associated with the use of seaweeds, the majority of which are consistent with government objectives such as the EU Green Deal, which targets more sustainable agriculture (Yıldız *et al*. 2021).

To reduce the risk of pollutants in seaweed, there is an ongoing effort from global stakeholders to create standard guidelines around the space and international limits for the identification and quantification of contaminants in seaweed-based animal feed, as well as the standardization of labels for seaweed-containing products. Interviewees highlighted how this would be beneficial for ensuring the continued growth of this sector.

Many farmers base their decisions on whether to adopt a product on the purchasing behavior of other farmers. Therefore, the adoption of more seaweed products in the feed industry will be influenced by veterinarians and farmers acting as trusted sources of information. In general, the adoption of new agricultural inputs typically relies on these networks, through which farmers expect to see practical evidence of use and efficacy. Without other stimuli, market growth may be limited by this process.

Technological developments

Although much of the technology is already in place for incorporating seaweed into livestock feed, the industry must evaluate the intra-species variability of seaweed composition, based on factors such as seasonality, environmental conditions, and geographical location. This will help determine the optimal inclusion level of seaweed in feed so that it is both effective for improving animal health and productivity and also palatable to the animals (WWF 2020).

It is also important to explore drying and processing techniques that can retain the desired compounds in seaweed, while still being economically viable. Dried and milled macroalgae are used as seaweed meal in animal feed. However, using fossil fuels to dry the biomass in an oven is energy-intensive and expensive, and alternative methods such as screw-press dehydration, and enzyme-assisted or microwave-assisted extraction, are being implemented.

In the context of using seaweed as a bulk source of protein, protein extraction from macroalgae can be challenging due to the complex polysaccharide cell wall and extracellular matrix, which varies significantly among species (Øverland *et al.* 2019). To overcome this, increased efforts around strain selection will be important for increasing protein content and post-processing yield. The development of more sophisticated, large-scale, innovative biorefinery processes have also been highlighted as an important milestone to be achieved in this sector.

Target geographies and investment requirements

To stimulate the animal feed and additive markets, the seaweed industry should prioritize production and processing, as there is currently a shortage of available seaweed. This includes investing in innovative drying solutions and finding suitable locations for decentralized farms.

Furthermore, it is important to use more seaweed species in order to spread risk and secure a consistent supply. This is necessary to fully understand and navigate the complexities of the industry. Consequently, investment should focus on several different species of brown, red and green macroalgae.

The investment required to establish a seaweed supply chain varies by location. For example, in Southeast Asia, the industry is said to be highly fragmented, with an underdeveloped processing infrastructure. However, multiple animal feed teams have made investments to provide critical equipment and address logistical challenges in the region. These investments help local communities with the initial costs of setting up sustainable harvesting and supply processes, and increase the seaweed supply.

To make seaweed-based feed products commercially viable and ensure the success and sustainability of their products in the market, organizations and governments need to focus on three key investment areas in particular:

1. **Research and development:** Companies in this sector perform regular animal field trials to demonstrate how their products work. This can be a lengthy and expensive process but is necessary to fully understand the value and effectiveness of their products. Once these new feeds have been tested at scale, companies are more likely to have the incentive to persuade veterinarians and farmers to implement the product. Greater recognition and acceptance by customers of feed efficacy and production, based on large-scale trials, is important. In addition, investing in LCA research would be beneficial for communicating the environmental benefits of this alternative supplement to stakeholders, and creating a positive public perception of the product. This may help attract more customers and increase market demand.

2. **Customer onboarding:** Onboarding new customers can take up to 12 months and often involves testing the feeds on a sample population of farm animals. This process depends on building good relationships with farmers, veterinarians, and consultants. Developing understandings and relationships with these consultants is critical, and that is where a strong sales team can make a difference.
3. **Supply chain:** Building up the supply chains is also important. Companies such as Ocean Harvest Technology, The Seaweed Company, and several other major players in this area have fully committed to vertical integration, which allows them to increase their margins and reduce risk by solidifying the supply of fresh biomass. Building processing facilities close to locations where seaweed can be produced at scale is important.

4.3. Pet food

Key highlights

Pet food

Seaweed is already used in the pet food industry, but no data on market size are available.

Global pet food market: $115.5 billion in 2022.

Projected market growth: 5.11 percent CAGR between 2022 and 2030.

Projected seaweed-based pet food market: $1.078 billion in 2030.

Key drivers

- The growing demand for vegan products with an emphasis on clean labeling, transparency, and sustainability.
- The growing preference for functional pet foods with augmented health benefits.

Main challenges

- Unavailability of sufficiently large volumes of seaweed.
- Highly consolidated market.
- Insufficient research to support health claims, excessively high mineral levels, contamination from pollutants, low palatability.

Outlook: According to our stakeholder interviews, this is a potentially more attractive market for seaweed producers than animal feed, particularly in areas where the cost of farming seaweed is high. Pet food products are generally more expensive than animal feeds, driven by the greater integration of domestic animals into the human family, and demand for healthy alternatives.

i. Introduction

Pet food is a subcategory of animal feed intended to be fed to domesticated companion animals such as dogs and cats. Pet food can be a complex composition of up to 60 ingredients (Thompson 2008).

BOX 3: PET FOOD MARKET DEFINITIONS

Prebiotics are non-digestible compounds found in high-fiber foods – oats, barley, wheat bran, beans, bananas, garlic, onions, almonds and seaweed, among others – that act as food for the good bacteria in the large intestines (gut), increasing their number and activity. They differ from **probiotics**, which are live microorganisms – typically derived from fermented foods such as yogurt – similar to the beneficial microflora found in the gastrointestinal tract, which has a microbiome made up of more than 1,000 types of healthy bacteria. In short, prebiotics act as food for probiotics. Probiotic foods help to replenish the good bacteria in the gut.

Functional ingredients or additives in pet foods are marketed as having special nutritional benefits in terms of general wellness or address specific health concerns – including digestion, joint and cartilage function, immune system strength, and dental health.

Pet food toppers are supplements, products, and ingredients that are mixed into an animal's meals. They are designed to boost the nutritional content or taste of canned and dry commercial foods.

ii. Seaweed's value proposition

Beneficial seaweed species for use in pet foods can be found in all three color categories – red, brown and green – of farmed and wild macroalgae. For example, carrageenans derived from cultivated red algae like *Kappaphycus* have been used in pet foods for decades as inexpensive thickeners, and a variety of seaweed species have been explored as protein sources (Waters *et al.* 2019). However, over the last few decades, one of the more interesting market applications has been the use of seaweed as functional feed ingredients or additives (see definitions in animal feed chapter) that offer specific gut health or digestive benefits for pets. This will be the focus of this chapter.

In the pet food industry, there is a focus on creating products that support digestive health. This can be challenging because digestion is influenced by various factors, including the balance of beneficial and harmful bacteria in the stomach (Nieuwenhuizen, C, 2019).) One solution companies have turned to is seaweed, which contains a range of bioactive polysaccharides, proteins and antioxidants which can influence pet health. Seaweed-derived polysaccharides – like alginate, fucoidan, laminarin and ulvan – are particularly attractive components in this regard and can act as prebiotics (Sands 2022).

Seaweed prebiotics have several potential applications in pet health, including improving gut health and suppressing the growth of harmful microorganisms. For example, studies have shown that consuming seaweed-derived pet supplements can improve the digestive or skin health of 88 percent of dogs (Sands 2022). Specifically, sulfated polysaccharides found in seaweeds like *A. nodosum* have been found to improve oral, fur, and skin health in dogs. The high content of soluble fibers in seaweeds can also provide a good substrate for hindgut bacteria. Consequently, companies around the world have been incorporating seaweed meal or extracts into pet food, pet treats, and pet nutritional supplements or toppers.

iii. Processing

Seaweed-based pet food ingredients and additives can be processed like conventional animal feeds (see Figure 9). Both intact and processed seaweeds can be used. Processing can involve drying and milling the seaweed, fermenting it, or may require more steps for enhancing or retaining certain components, improving digestibility, or removing hazardous compounds and antinutritional factors.

As outlined in the animal feed section, the fermentation of seaweed involves using microorganisms to enhance its properties and help make it more stable for storage. For example, the company Seadling germinates, raises, and cultivates *Kappaphycus* sp. with partner farmers. After harvest, the seaweed undergoes fermentation to increase its nutritional value, leading to higher levels of phytochemicals and amino acids. It is then dried, processed, tested, and shipped to buyers, where it can be applied as a supplement or feed additive (Seadling n.d.).

The conversion ratio between wet seaweed and final feed product depends on the level of processing, seaweed species, and season. As highlighted in the animal feed section (chapter 4.2), this can range anywhere from 2 to 25 percent. To account for this variation in conversion ratios, we assume 1 ton of fresh seaweed yields about 100 kg of seaweed pet food (10 percent).

iv. Market overview

The total volume of pet food produced in 2021 was around 34 million tons (see Table 10 below). Europe and North America are the largest markets, accounting for 34 percent and 31 percent of global production, respectively. Dogs and cats make up the biggest segments of the market.

TABLE 10: Global pet food production volumes in 2021 and 2020

Region	Sum of 2020 Feed Tonnage: Pet (MMT)	Sum of 2021 Feed Tonnage: Pet (MMT)	Var. 2020 to 2021 (MMT)	Growth (%)
Africa	0.444	0.454	0.009	2.1%
Asia-Pacific	3.256	3.813	0.557	17.1%
Europe	11.280	11.587	0.307	2.7%
Latin America	6.671	7.184	0.513	7.7%
Middle East	0.075	0.075	-	0.0%
North America	9.409	10.600	1.191	12.7%
Oceania	0.452	0.452	-	0.0%
Grand Total	31.587	34.165	2.578	8.2%

Source: Alltech Agri-food Outlook (2022)

The global pet food market was valued at $115.5 billion in 2022 (Fortune Business Insights 2022a). As a segment of that market, the functional pet food market was valued at $1.95 billion in 2020, and by 2030, it is forecast to reach $4.68 billion, growing at 8.8 percent CAGR (Allied Market Research 2021). Globally, the market is highly consolidated and dominated by multinational companies, such as Mars Petcare, which generated over $19 billion in revenue in 2021, and Nestlé Purina PetCare, which generated around $16.4 billion in revenue in 2021 (Bedford 2022).

TABLE 11: Pet food retail value sales in the selected countries (US$ millions, year-over-year exchange rates historical and forecast

Market	2016	2020	CAGR* % 2016–2020	2021	2025	CAGR* % 2021–2025
Total	12,384.3	13,677.5	2.5	14,204.3	17,203.4	4.9
Japan	3,804.5	4,065.2	1.7	4,167.5	4,625.9	2.6
Canada	2,555.0	3,100.1	5.0	3,281.0	4,110.4	5.8
Australia	2,471.0	2,626.3	1.5	2,677.6	3,188.3	4.5
Mexico	1,876.0	2,012.3	1.8	2,131.5	2,912.1	8.1
Chile	758.5	822.5	2.0	845.8	1,012.7	4.6
New Zealand	426.1	424.3	−0.1	433.3	468.2	2.0
Peru	219.4	274.7	5.8	292.4	397.7	8.0
Malaysia	165.1	204.5	5.5	216.9	280.4	6.6
Singapore	78.0	91.7	4.1	96.0	111.9	3.9
Vietnam	29.5	54.5	16.6	60.9	94.2	11.5
Brunei	1.2	1.4	3.9	1.4	1.6	3.4

Source: Euromonitor (2021); https://agriculture.canada.ca
Note: CAGR: Compound annual growth rate

Key markets for pet food include affluent Western countries and several developing regions with high pet ownership and populations. For example, the American Pet Products Association's National Pet Owners Survey found that dog-owning households in the US are increasingly focused on purchasing nutritious food (Mordor Intelligence 2021a). Meanwhile, Asian and South American regions show increasing interest in premium pet treats, particularly for small dogs.

Prices of dog food products vary, according to composition and premium status. In the US, prices per pound (lb.) of dog foods sold directly to consumers are highlighted in Figure 11.

Typically, there are three different price ranges – cheap dog food for $1.50 per lb. or less ($3.3 per kg or less), mid-range dog food for $1.51 to $2.00 per lb. ($3.31 to $4.44 per kg), and expensive dog food for over $2.00 per lb. (over $4.45 per kg). However, pet foods that incorporate functional ingredients with augmented health benefits can cost more than $20.5/lb dry weight.

Meanwhile, prices for pet treats and prebiotic supplements or nutraceuticals can be much higher. Common prebiotics are:

1. Fructo-oligosaccharides (FOS) – derived from fructose molecules in fruit and root vegetables.
2. Mannan oligosaccharides (MOS) – from the yeast *Saccharomyces cerevisiae*.
3. Galactooligosaccharides (GOS) – found in dairy, beans, and root vegetables.
4. Inulin – indigestible starch found in many fruits and vegetables.

Supplements for these prebiotics can come in powders, treats, chewable pills, or capsules, and can be sold at prices far exceeding $50 per 100g (petcubes 2023).

FIGURE 11: Variation in pricing of dog food brands (1lb is 0.453592kg)

Source: Woof Whiskers (2023)

v. Market dynamics

Drivers

Growth in the market is driven by a number of factors, including a shift toward treating pets as family members and a desire to provide them with high-quality products. The consumer trend of “humanizing” pets has led to the development of more sophisticated snacks and treats (Williams 2019). There is an increasing preference for functional treats, which offer additional health benefits, and large corporations have been developing new functional treats to meet demand (Mordor Intelligence 2021a, 2021b).

The pet food market continues to be influenced by trends in the broader food industry. The strong emotional bond between humans and their pets has contributed to an emphasis on clean labeling, transparency, accountability and sustainability. These trends present opportunities for companies to develop new, vegan products that appeal to pet owners. The growing demand for locally produced and ethically sourced products has motivated many of these larger corporations to develop more production plants closer to major markets (Coriolis 2014). Incumbent players, such as Nestlé, are responding to consumer demand by introducing new offerings that incorporate sustainable ingredients like microalgae.

An incumbent in this space is Acadian Seaplants, which produces the pet food product Tasco. Tasco incorporates wild-harvested *A. nodosum*, and has over two decades of scientific research supporting its use as a pet-friendly seaweed (Pet Food Industry 2019). It can be incorporated as a pet food ingredient or supplement (Kandasamy *et al.* 2011). Additional organizations in the space include The Seaweed Company and Ocean Harvest Technology, who are producing pet foods alongside animal feeds using cultivated seaweeds.

New innovators in the field, such as Seadling and Blue Pet Co., have also recognized the opportunity in this sector. Seadling is focused on fermented, cultivated seaweed supplements, while Blue Pet Co is introducing a line of zero-carbon supplements made with hand-harvested seaweed using a bioprocessing technique that extracts and concentrates unique molecules such as fucoidan.

Several corporations recognize that macroalgae may be a more sustainable source of ingredients compared to land-based materials like soy or livestock meat. Across pet foods, there is a general need to improve sustainability by reducing cropland and water usage. In the United States, 1 ton of pet food uses approximately 851 ha of cropland and 686,821 KL of water (Acuff *et al*. 2021). In addition, a recent study explains that annual global dry pet food production is associated with 56–151 million tons of CO_2-equivalent emissions per year (1.1–2.9 percent of global agricultural emissions) (Alexander *et al*. 2020). This is equivalent to the total annual emissions from Mozambique.

Seaweed could be used to reduce the carbon and water footprint of the sector, and several companies have been investigating this potential. However, there are concerns about the potential for contaminants, such as heavy metals, in seaweed products sourced from polluted areas. This presents an opportunity for companies that can provide a clean, sustainable source of seaweed for the pet food industry.

Prices and volumes

Table 12 shows the prices of several high-value seaweed products. Seaweed products sold directly to consumers can cost upward of $100/kg when sold as a treat or supplement. An alternative business model is B2B – in these instances, some of the stakeholders interviewed mentioned that fermented seaweed can sell for about $10/kg to pet food manufacturers.

TABLE 12: A selection of pet treat and supplement products

B2C Product type	Pet food product	Seaweed inclusion %	Total product price retail ($/kg)	Main functional components
Pet food ingredient in treats	GoShine – Blue Pet Co (https://bluepetco.com)	5.07	106	1. PhyCoidan complex (seaweed meal) is derived from *Fucus vesiculosus*, and enriched with fucoidan, natural antioxidant marine polyphenols, vitamins and minerals. 2. PhytoMara (seaweed meal) extracted from *A. nodosum* seaweed, enriched in the laminarin, fucoidan, alginate and polyphenols.
Pet food ingredient in treats	GoSmile – Blue Pet Co (https://bluepetco.com)	3.85	53	PhytoDent (seaweed meal) is a blend of *A. nodosum* and *Fucus vesiculosus*. Enriched with fucoidan.
Pet food topper supplement	Prebiotic fermented supplement-Neptune's Yard (https://neptunesyard.co.uk)	100	71.964	Fermented *Kappaphycus alvarezii.*

Table 12 illustrates how the inclusion of high-value carbohydrates extracted from seaweed, such as fucoidan and alginates, can add value to pet food products. In the case of Blue Pet Co, adding just 50 grams of seaweed meal per kilogram of pet food (consisting otherwise of ingredients such as whole peas, dehydrated chicken, oats, coconut oil and molasses) can help pet foods sell for significantly higher prices.

Unfortunately, production at scale is not common in most areas outside of Asia. This is a challenge for leading pet food producers, who seek high volumes of seaweed for use as thickeners and functional ingredients. Our interviewees suggested that larger organizations, including M&M Mars, have sought out seaweed in developing markets with potentially less polluted waters. However, these companies often require a reliable, sustainable source of around 2,000 tons of wet seaweed per order.

vi. Competition

The global pet food market is highly consolidated. According to our interviews, there has been significant interest in incorporating more seaweed into the supply chains of major pet food companies. Whether this will be in the form of functional food, or as a means of enhancing the sustainability of operations through the use of products such as seaweed biostimulants, remains to be seen.

There are several sustainable alternatives to using seaweed in pet products. Insects and microalgae, for instance, have both been explored as sources of protein and functional ingredients. Nestlé recently partnered with Corbion to use microalgae in various products (Nestlé 2019). Corbion has been an advocate for using long-chain, omega-3s derived from microalgae, which can enhance neurological, immune, fertility, and vascular health in animals (Corbion 2022). Another alternative to seaweed pet food is rendered meat and bone scraps, obtained from animal agriculture and grocery store leftovers and used to make high-quality protein for pet food. However, rendering is not without its sustainability concerns, as it involves the use of animal parts that originate from high carbon-footprint industries (Industry 2019). Meanwhile, the Biomega Group, based in Norway, has created a technology that uses salmon waste to provide pets with protein, omega-3 fatty acids, and other essential nutrients (Pet Food Industry 2019). Bond Pet Foods, in Colorado, has also been employing biotechnology to create animal-free pet food using a novel, dried-yeast protein (Berry 2021).

These products can outcompete seaweed from a protein perspective, but the acceptability of these alternatives as pet food ingredients may vary in different cultures and locations (McCusker *et al.* 2014). In addition, from a functional treat perspective, seaweeds have unique benefits, including the presence of bioactive compounds such as fucoidan.

Challenges

Seaweed-derived pet foods face challenges similar to those of animal feed products (see chapter 4.2). For example, not all species of seaweed are suitable sources of biomass. Factors such as efficacy, palatability, nutritional limits, and compliance with regulations are potential obstacles for new entrants into the market. Many seaweed species have insufficient research to support health claims, and others have undesirable characteristics – such as high mineral levels, contamination from pollutants, or low palatability (PetfoodIndustry.com 2019). The nutritional quality of plants and macroalgae can also vary based on factors such as season, location, and environmental stress (McCusker *et al.* 2014).

In addition, there are challenges relating to inadequate supply, as mentioned in the common section of this report. Our interviewees mentioned that large pet food manufacturers often demand shipment volumes that emerging seaweed regions, where production volumes equate to under 1,000 tons, cannot yet meet. Meanwhile, in the established markets, products like carrageenan already absorb the entire current supply of macroalgae. To address this supply challenge, companies must establish strong supply relationships and consider investing in, or vertically integrating, their supply chain.

Regulation

In terms of regulation, there are certain controls for pet food products. For example, the EU has established guidelines for acceptable feed materials in pet food, including algae products. For instance, the maximum level of arsenic in macroalgae feed materials is 10 mg/kg for complete and complementary feed for pets (Lähteenmäki-Uutela *et al*. 2021). This is an important consideration and potential barrier to entry when choosing seaweed species and markets to target. Nevertheless, according to our interviewees, these regulations are generally not considered major hurdles.

vii. Market outlook

The global pet food market is projected to grow at a CAGR of 5.11 percent to 2030. Seaweed is already used in the pet food industry, and based on our analysis of key drivers and dynamics, the seaweed-based pet food market is projected to reach $1.078 billion by 2030.

In the pet food industry, data and targeted marketing can drive the adoption of seaweed products in the coming years. In addition, a blend of species can offer greater benefits and mitigate negative effects, like varying levels of heavy metals. Consequently, to maximize the benefits and minimize risks, teams could aim to make blended seaweed products more mainstream. Our interviewees suggested this would accelerate an improvement in attitude toward these products.

According to our stakeholder interviews, scaling seaweed farming in emerging regions is important for seaweed to compete more in the pet food category. As seaweed farming operations gain public acceptance and secure necessary permits, the cost of production is expected to decrease, leading to wider market adoption. This will allow farms to provide pet food companies with a sufficient volume of seaweed for reliable product development.

Currently, seaweed blends supplied by larger corporations are minimally processed and can be certified organic. These qualities make seaweed blends an ideal fit for clean label, natural and sustainable pet food diets. However, to advance the pet food industry, technological developments should focus on more sophisticated fermenters, biorefineries and scaling supply (Pet Food Industry 2019).

In addition, major purchasers of seaweed for pet food are demanding improved traceability and assessment of environmental benefits. The industry-wide push for more life cycle analyses (LCAs) will allow for an evaluation of the environmental impacts of pet food production systems (Acuff *et al.* 2021). This will bolster claims that seaweed is an environmentally sustainable pet food ingredient, which is a significant driver for buyers.

According to our interviewees, stakeholders are largely interested in seeing an asymmetric distribution of investment funds. A significant proportion should go toward strain selection and establishing seaweed farms. Another large proportion should go toward the development of new policies, regulations and incentives. Marketing efforts should receive a smaller investment, as the focus should be on achieving cost-effective processing and integration into the supply chain.

4.4. Methane-reducing feed supplements

Key highlights

Methane-reducing feed supplements

There have been limited commercial sales of methane-reducing seaweed additives.

Global methane-reducing additive market: $47 million in 2022.

Projected market growth: 57 percent CAGR between 2022 and 2030

Projected seaweed-based market potential: $306 million in 2030.

Primary drivers

- Demand from consumers for more sustainable meat and dairy products, coupled with net-zero policies from corporations.
- Economic incentives: potential productivity gains and route to monetization using carbon crediting pathways.

Main challenges

- Availability of sufficient seaweed volumes.
- For many companies, there is single species risk, as cultivation of *Asparagopsis* is neither widely practiced nor deeply understood.
- Speed of regulatory approval in many geographies may be slow, unless more time is spent on increasing awareness.

Potential deal-breaker challenges

- Competition from synthetics

Outlook: Stakeholders predict that time to commercial scaleup is only a couple of years away. There is clear market demand for this product and the sector is attracting significant investment to overcome these challenges. This momentum may allow the challenges to be overcome faster than for other markets, as long as unsubstantiated claims are avoided.

i. Introduction

In ruminant animals, volatile fatty acids (VFAs) produced through the fermentation of simple and complex carbohydrates by rumen bacteria can provide over 70 percent of the host animal's energy needs. Unfortunately, the enteric production of some VFAs also generates hydrogen (H_2), which is then used by methanogenic archaea to produce methane (CH_4). Methane has a global warming potential (GWP) 28 times greater than that of carbon dioxide (CO_2) by unit. For this reason, it is the main direct source of GHG emissions in beef and dairy production. In the US alone, it is estimated that enteric fermentation accounts for approximately 2.7 percent of anthropogenic (that is, human-caused) GHG emissions (26.7 percent of CH_4 emissions) (Vijn *et al*. 2020). In recent years there has been a concerted focus on developing methane mitigation strategies for ruminants. A promising strategy might be diet modification through feed additives that can reduce methane emissions in ruminants (Palangi and Lackner 2022).

BOX 4: METHANE-REDUCING FEED SUPPLEMENTS: MARKET DEFINITIONS

Bromoform: A naturally-occurring bioactive compound produced by seaweed, it has been found to dramatically decrease the production of methane when added to the feed of livestock.

Anthropogenic emissions: Emissions of GHGs, the precursors of GHGs, and aerosols through human activities, such as fossil fuel combustion, deforestation, and cattle farming.

Methanogenesis: A form of anaerobic respiration performed by microbes called methanogenic archaea that uses carbon as an electron acceptor, resulting in the production of methane. Anti-methanogenic supplements can inhibit methanogenesis in ruminant animals (cattle, buffalo, sheep, goats and camels).

Enteric fermentation: Fermentation that takes place in the digestive systems of animals. Ruminant animals have a large "fore-stomach," or rumen, within which microbial fermentation breaks down food into soluble products.

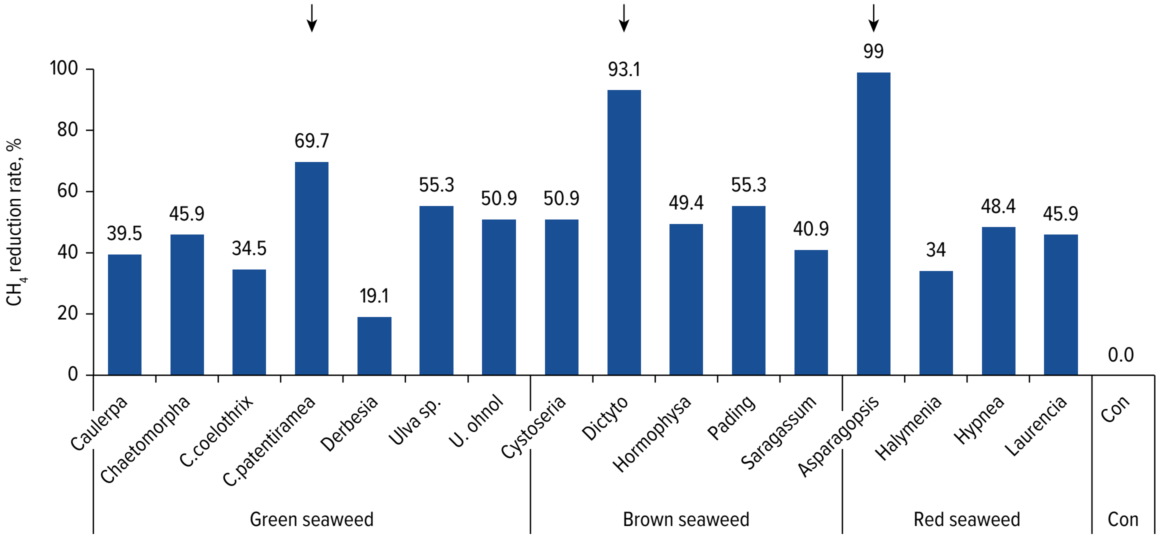
Feedlots: Yarded areas where cattle are held in groups in close confinement while receiving feed. Feedlots are used in beef production to ensure that cattle reach a specific weight before slaughter and to provide consistent meat quality and quantity to meet consumer demand. By contrast, **grazing** is a method of animal husbandry in which domestic livestock are allowed to roam around outdoors and consume wild vegetation. **Cut and carry**, sometimes referred to as zero grazing, is a feeding system where fresh grass is cut daily and fed to housed cows throughout the grazing season.

Dairy cows: Cattle bred to produce milk. Most dairy cows are kept indoors for part, or all, of the year.

ii. Seaweed's value proposition

Seaweeds such as *Asparagopsis taxiformis, Asparagopsis armata, Alaria esculenta, A. nodosum*, and *Chondrus crispus* can reduce CH_4 emissions in ruminants when applied as feed supplements, as shown in Figure 12.

FIGURE 12: Inhibition of CH4 emission by ruminants through application of *Cladophora patentiramea* (green seaweed), *Dictyota* (brown seaweed), and *Asparagopsis* (red seaweed) additives



Note: *Cladophora patentiramea*, *Dictyota*, and *Asparagopsis* were shown to inhibit methane production in vitro by 69.7 percent, 93.1 percent and 99.0 percent, respectively (Min *et al.* 2021).

Asparagopsis has shown particularly high GHG reduction potential (see Figure 16). This is largely attributed to the chemical bromoform, which is produced naturally during the *Asparagopsis* life cycle. Bromoform inhibits methanogenesis by blocking the activity of enzymes involved in the Wolfe cycle, which governs the conversion of CO_2 into CH_4. However, bromoform is not responsible for the methane-reducing capacity of all seaweeds. Patra and Saxena (2010) have reviewed how saponins, tannins, flavonoids and organosulfur compounds all demonstrate the potential to reduce CH_4 emissions. Tannins and phlorotannins, in particular, have been highlighted as promising anti-methanogenic components found in brown seaweeds (Wasson *et al.* 2022). However, research on these compounds is in its early stages and many alternative compounds have not yet been tested *in vivo* (Wasson et *al.* 2022).

Asparagopsis appears to be the best candidate because of its effectiveness even at low inclusion rates (Wasson *et al*. 2022). Adding small amounts (0.2 percent inclusion rate) of *A. taxiformis* to the diets of beef steers can reduce CH_4 emissions by up to 98 percent (Kinley *et al*. 2020). *In vivo* supplementation of *A. taxiformis* (0.5 to 3 percent organic matter (OM) basis) in sheep also reduced CH_4 emissions by up to 80 percent over 72 days (Li *et al.* 2018). Consequently, most commercialization efforts using seaweed have centered on *Asparagopsis*.

This high level of emission reduction effectiveness can help to make beef, dairy, leather and wool production more sustainable. As little as 20 percent market penetration of *Asparagopsis* across the major Organization for European Economic Co-operation (OEEC) nations in beef and dairy feed could remove up to 15 percent of total global enteric CH_4 emissions (Kinley *et al.* 2020).

In addition, intercepting methanogenesis diverts energy to the growth of the animal because methanogenesis is responsible for energy losses of up to 12 percent of the total feed energy in ruminant livestock (Glasson *et al.* 2022). Reducing this process results in improved output for less feed, which can reduce the total operating costs for feedlot and dairy farming.

iii. Processing

Several companies are trying to commercialize this property of seaweed by creating anti-methanogenic seaweed-based supplements. A common pathway for processing *Asparagopsis* involves applying a saltwater rinse, spin drying, freezing at -80°C, and then freeze-drying. Freeze-drying is effective at retaining the content of antioxidants, phenols, vitamins and other bioactives in natural products. This resulting product has a high bromoform content (Tan *et al*. 2022). To date, freeze-drying *A. taxiformis* yields a higher concentration of bromoform than other processing methods.

Jia *et al*. 2022 state that when *Asparagopsis* is prepared in this way, there is a 15:1 fresh weight to dry weight conversion. Effective CH_4 reduction in ruminants requires a daily feed dry matter intake (DMI) of about 0.4percent freeze-dried and milled *A. taxiformis*. This amounts to daily feed additions of 38g dry weight (DW) *Asparagopsis* per head of feedlot cattle, and 94gDW *Asparagopsis* per head of dairy cattle (Jia *et al.* 2022).

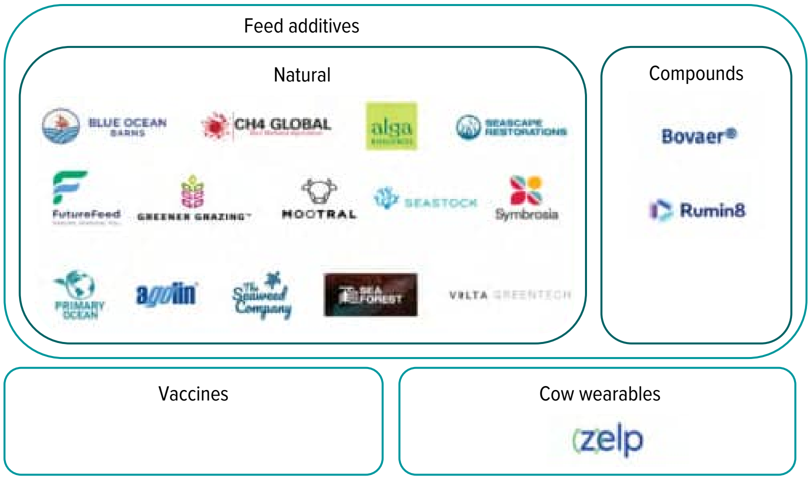
Oil immersion has been highlighted as a suitable alternative way to process *Asparagopsis*. According to experiments by Magnusson *et al.* (2020), the most effective method to create a stable bromoform product in this way involves homogenizing *Asparagopsis* in the oil, as opposed to immersing the biomass intact. Homogenizing 120g of *Asparagopsis* in 100ml of oil (ratio of 1.2:1) was deemed optimal (Magnusson *et al*. 2020). The oils can then be sprayed on the grain fed to cows daily (Macdonald 2023). The company SeaForest has previously described how it employs this technique – delivering seaweed immersed in canola oil to its customers – instead of freeze-drying.

iv. Market overview

Stakeholders indicated that global sales of methane-reducing feed amounted to just $30 million in 2021. It is predicted, however, that the global market for these products will reach $1.18 billion–$2.37 billion by 2030 (Nickel 2020). Using this growth rate and using 2021 as a base, we estimate that market value in 2022 was approximately $47 million in 2022.

Ruminant methane-reducing product segments include natural supplements (seaweed and essential oils), synthetic compound supplements, vaccines, and cow wearables. As shown in Figure 13, a number of innovators are developing a range of anti-methanogenic feed supplements.

FIGURE 13: A selection of innovative companies developing anti-methanogenic solutions for ruminants



Source: Purdom and Zou (2022)

Bovaer is the commercial name for the synthetic compound 3-nitrooxypropanol (3-NOP), manufactured by the DSM. There is robust evidence that it has a high (>25 percent) efficacy in reducing enteric methane production in cattle (Hegarty *et al*. 2021a). Bovaer is now widely authorized and available for sale in over 40 countries, including the EU/EEA, Argentina, Brazil, Pakistan and Australia (DSM 2022). Data for overall sales was not available. However, for dairy, the costs for the farmer have been reported as $85–$95 per cow, per year – until Bovaer can be scaled through DSM's new production plant in Scotland, which could help bring the price down to between $53 – $58 per cow, per year (Bodde 2022; Government of Ireland 2022) . Other estimates by DSM state that Bovaer will cost between $0.27 and $0.34 per head per day for feedlot cattle, depending on volume (Barker 2022). According to our stakeholder interviews, this is above the upper limit of what most farmers are prepared to pay for an additive. In the livestock industry, $0.14 per day, per animal, is said to be the maximum farmers would pay (Borrello 2023).

TABLE 13: Seaweed alternative key anti-methanogenic products available on the market

Product name	Product type	Available price indicators	Availability and notes
SilvAir (by Cargill)	(Calcium) Nitrate	About $0.14 per cow per day (Byrne 2022). Other estimates suggest calcium nitrate costs $730/ton (Hegarty *et al*. 2021a)	Already available and used in commercial demonstrations in Brazil and Europe.
Agolin	Essential oil blends of plant extracts that include wild carrot and coriander seed oil	Between $0.04 to $0.06 per cow per day (Schmitz 2021)	It is estimated that in 2021, it was fed to 1.5 million dairy cows worldwide. Major milk buyers Nestlé and Barry Callebaut have partnered with the company and dairy cooperatives to encourage its adoption (Schmitz 2021).
Mootral (by Mootral)	Essential oil blends – allicin (from garlic) and citrus extract	$0.17 to $0.21 per cow, per day (van Osdol 2022)	Mootral sells their product directly to farmers. They have a handful of initial flagship farm clients, like Brades Farm. Mootral has a carbon credits program for enteric methane reduction from cattle, called CowCredit; 1 CowCredit = 1 t CO_2e reduction, which can co-finance the cost of Mootral for ruminants through selling the credits on voluntary carbon markets (Hegarty *et al.* 2021a). Mootral's carbon offsets trade at a premium compared to other products on the market (up to about $75 in 2023), but selling the carbon credits would help to underwrite its costs so that Mootral can supply the supplement to farmers for free (van Osdol 2022).
Monensin	Antibiotic rumen modifiers	Monensin (active ingredient) is approximately $28/kg	An antibiotic used widely and globally but prohibited in the EU.
Rumin8	A synthetic product derived from bioactives in *Asparagopsis* seaweed	$0.18 per cow per day (target)	Rumin8 is still in its testing phase. In late 2022, the company set out to trial the product for 130 days in Brazil (Büyükkılıç 2022).

Intensive-feed industries that are exploring feed additive products include feedlots, cut and carry, and dairy (Hegarty *et al.* 2021).

Grazing systems will likely be the last to adopt many of these products and are not a high-priority market for methane mitigation products. Much of this results from a lack of suitable delivery processes and a lack of control of feed intake (Hegarty *et al*. 2021a).

Most companies developing seaweed feeds in this sector are cultivating *Asparagopsis* – either the tropical *A. taxiformis* or the temperate *A. armata*. Cultivation is currently being performed both in marine environments and land-based systems, where growth conditions can be more carefully controlled. The *Asparogopsis* life cycle consists of three stages: gametophyte, carposporophytes, and tetrasporophytes. All three phases can be sustained in aquaculture, but there have previously been challenges in closing the life cycle, largely because of the difficulties of triggering spore release in aquaculture facilities. Several startups including SeaForest and CH4 Global have since made announcements that they have achieved this milestone using a combination of land-based and ocean-based farming practices. Meanwhile, the company Greener Grazing has been demonstrating how to close the life cycle of *A. taxiformis* using ocean-based grow-out.

The company FutureFeed owns the rights to the patents of *A. Taxiformis* and the company has licensed its technology to several companies around the world including:

1. Greener Grazing – Vietnam
2. Sea Forest, SeaStock, Immersion Group and CH4 Australia – Australia
3. Blue Ocean Barns, Symbrosia, CH4 Global – US
4. Volta Greentech – Europe

Meanwhile, innovative startups and early stage companies – such as The Seaweed Company, Cascadia Seaweed and Alga Biosciences – have been investigating alternative seaweeds like sugar kelp (*Sacchariatissimiima*) for their anti-methanogenic properties. This approach would avoid the introduction of non-native *Asparagopsis* species to new environments (*Asparagopsis taxiformis* is supposedly native to Australia and New Zealand). According to our interviewees, these trials have shown some methane reduction and feed conversion improvements. However, they also highlighted that *Asparagopsis* supplements remain the most effective at methane reduction.

As highlighted by the table above, there are a number of larger organizations closely monitoring, building and investing in the anti-methanogenic market. This stems from their desire to reduce lifecycle emissions for their products and supply chains. Examples of these organizations include:

1. **Large feed production companies:**
   a. DSM and Cargill have both developed methane-reducing products (Bovaer and SilvAir).
2. **Large-scale feedlot and dairy farmers**:
   a. In 2020, Fonterra entered into a partnership with Sea Forest to test *Asparagopsis* solutions on dairy cows.
3. **Corporate groups**:
   a. **Supermarkets:** Morrisons UK have been closely investigating anti-methanogenics derived from seaweed native to the UK.
   b. **Restaurants:** Burger King recently stated that they were adding lemongrass to cow feed as an anti-methanogenic.
   c. **Food and drink companies**: Ben & Jerry's recently signed a partnership deal with Blue Ocean Barns for seaweed-derived anti-methanogenics. Starbucks has also invested in Blue Ocean Barns, via Valor Siren Ventures, while Danone recently invested in Symbrosia.

v. Market dynamics

Drivers

Primary drivers behind the anti-methanogenic supplement market include:

1. **Demand from consumers for more sustainable products** – especially meat and dairy. Big retailers and fast-moving consumer goods (FMCG) brands – such as Woolworths and Ben & Jerry's – have responded by setting net-zero policies (Schroder and Amadeo 2022). Farmers are incentivized to partner or collaborate with these large organizations in achieving these goals.
2. **Economic incentives**: potential **productivity gains** through improved feed conversion ratios with seaweed are a key motivator for farmers. Large-scale trials are currently being performed to validate the feed conversion improvements in cattle. **Carbon crediting** is also a viable route to monetization. Companies in the methane-reduction supplement category have already submitted proposals or registered with carbon credit certification schemes. This will incentivize farmers to adopt these additives. However, who will claim the offset remains contentious (Purdom and Zou 2022).
3. **Compatibility and short time-to-impact**: the effects of feed additives can be seen quickly and can be implemented with fewer disruptions than other potential solutions to reducing methane production by cattle.
4. **Regulatory pressure from governments**: for example, New Zealand's government recently proposed taxing the greenhouse gases that farm animals release.
5. In addition, farmers in several regions – including Australia's entire **red meat industry** – have set goals of becoming carbon neutral by 2030, and the use of *Asparagopsis* as a feed supplement is one way that this goal can be achieved.

Seaweed prices and volumes

It is difficult to accurately predict the commercial performance and pricing of *Asparagopsis* products, as some companies are hesitant to provide specific estimates, because of the sensitive nature of this information. However, as organizations begin commercial production in the next few years, more concrete price points will become available.

In the past, price estimates for *Asparagopsis*-based feed additives have varied, with some early stage startups highlighting pre-scaling price points ranging from $0.80 to $1.50 per animal per day. The target for some startups in 2019 was selling directly to livestock feed suppliers for $3.5/kg dry weight (Winn 2019). Meanwhile, stakeholders working with later stage startups like Sea Forest have said that the product currently costs around $0.62 per cow, per day (Macdonald 2023).

According to our more recent interviews, some early-stage startups are currently selling *Asparagopsis* feed additives for $30/kg. As they scale up, a price around $20/kg dry weight was suggested. At scale, several stakeholders stated that the product will likely cost around $10/kg dry weight. Our interviewees suggested that this price reduction would help bring the product price down from $1 per beef cow per day, down to around $0.30 per cow per day.

As noted previously, this price will generate resistance from average farmers, who are hoping to pay no more than $0.15 extra per head per day. However, if government subsidies and carbon credit schemes are developed to support farmers, that will likely change. In addition, larger scale animal feed conversion ratio studies – such as Kinley *et al.*'s recent demonstration that inclusion of *A. taxiformis* at a 0.5 percent rate can increase total feed efficiency in beef cattle – could help sway buyers (Roque *et al.* 2021). Depending on the seaweed dose, the study suggests that a producer finishing 1,000 head of beef cattle could potentially save between $40,320 (low) and $87,320 (high) per year. There is a call for further research in a larger feedlot context to reduce animal variability.

In terms of volumes required to service the sector, cultivating *A. taxiformis* can be a challenge, as the species is not yet fully understood. This also makes it difficult to predict future yields for large-scale production. However, current estimates in Australia suggest yields of 2–2.5 tons dry weight per hectare (combined ocean and terrestrial production), while more optimistic targets of 10 tons dry weight per hectare have also been proposed (Ball *et al*. 2022; Taylor 2021; Zhu 2021). Based on these estimates, Ball *et al*. suggest that between 2,656 ha and 10,626 ha would be necessary to produce 26,565 tons of seaweed per annum – enough to meet the supplement needs of the 2.9 million feedlot cattle in Australia that are slaughtered each year (Ball *et al*. 2022).

According to one study, approximately 3–3.4 million tons of dried seaweed would be required annually to feed all 93 million cattle in the US at a 1 percent inclusion level (Vijn *et al*. 2020). Scaled down, this equates to a yearly demand for 36,559 tons of dry seaweed per million cattle. Another study estimated that servicing 1.1 million cattle in Australia would require approximately 26,500 tons of dry seaweed (Ball *et al*. 2022).

Competition

As outlined in the market overview, competition in the anti-methanogenic market comes from a range of natural products and synthetic compounds.

Only two of the additives – Bovaer and *Asparagopsis* – have routinely delivered over 20 percent mitigation of enteric methane by the consuming ruminants (Figure 14). DSM's synthetic Bovaer 3-NOP, has been shown to achieve a 30 percent reduction in methane emissions.

Although *Asparagopsis taxiformis* has shown the most promise in overall reduction of methane emissions, Bovaer is further down the regulatory track than *Asparagopsis*, having been approved in more than 40 countries, including the EU. It took almost a decade from first patent to first approval (Macdonald 2023).

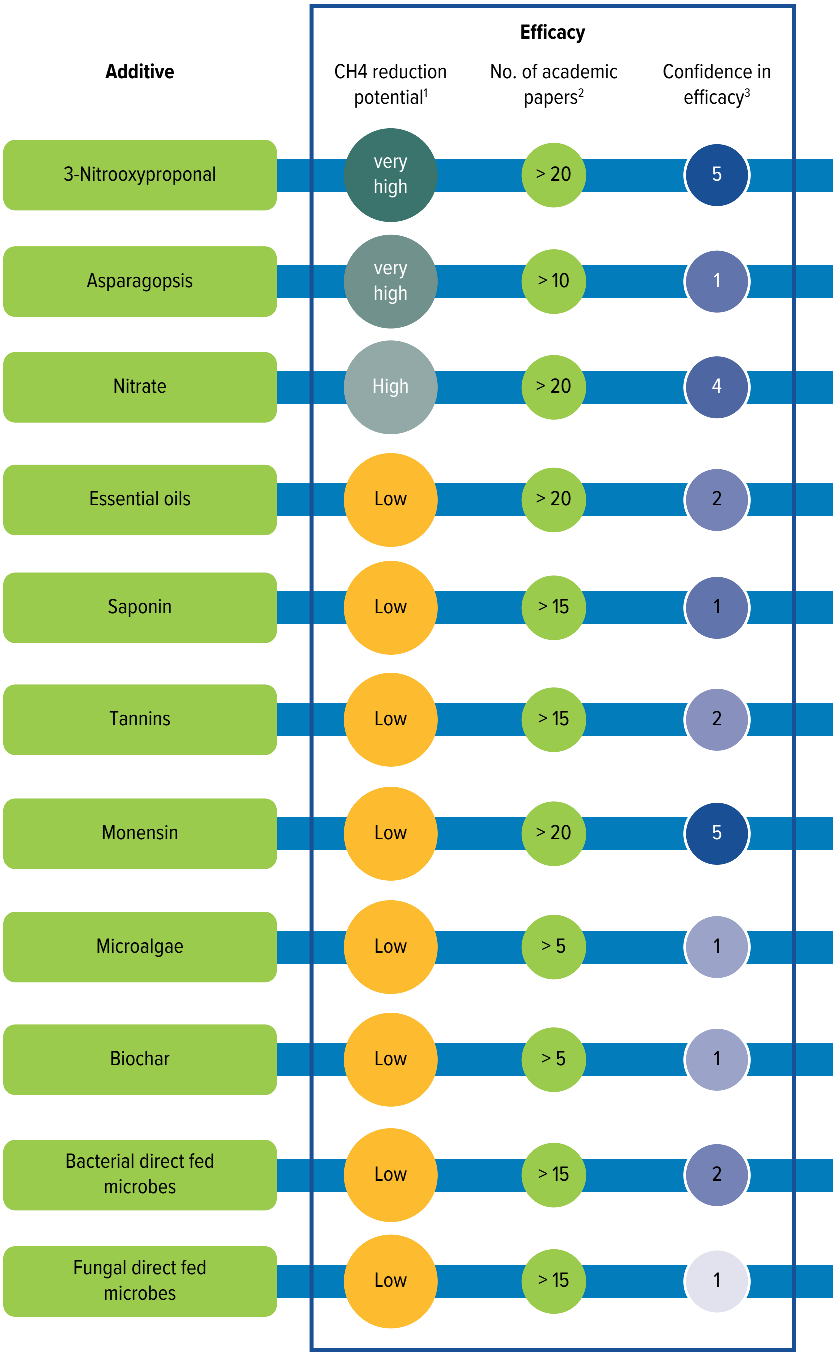
In addition, both ocean and land-based farming of *Asparagopsis* have growth challenges. Companies like Rumin8 are trying to circumvent these challenges by synthetically reproducing the anti-methanogenic compounds, instead of mass producing the seaweed itself. This has attracted attention from investors, but several of our interviewees noted that there were additional challenges involved in bringing synthetic products to market compared to natural ones.

An alternative route to address cultivation challenges for the seaweed sector might involve combining *Asparagopsis* with low-cost algae like kelp, which also has bromoform content and could reduce costs while maintaining effectiveness (Khoury 2021).

Anti-methanogenic vaccines are still in the early stages of development, but have the potential to be highly valuable, as they can be administered infrequently and do not require any changes to farming practices.

In general, many stakeholders advocate for multiple solutions, as they recognize that the challenges facing each product type are different.

FIGURE 14: List of competitors for methane reducing feed additives



Additive	Efficacy CH4 reduction potential[1]	Efficacy No. of academic papers[2]	Efficacy Confidence in efficacy[3]
3-Nitrooxyproponal	very high	> 20	5
Asparagopsis	very high	> 10	1
Nitrate	High	> 20	4
Essential oils	Low	> 20	2
Saponin	Low	> 15	1
Tannins	Low	> 15	2
Monensin	Low	> 20	5
Microalgae	Low	> 5	1
Biochar	Low	> 5	1
Bacterial direct fed microbes	Low	> 15	2
Fungal direct fed microbes	Low	> 15	1

Source: Hegarty *et al*. (2021a)

Challenges

1. It is important to consider the potential for invasive species to be introduced to new regions through farming of anti-methanogenic seaweeds. As mentioned above, *A. taxiformis* is not native to all geographies. It will be crucial to pursue regional solutions that consider local environmental information and the potential impact of introducing non-native species.
2. There is a need to monitor the long-term effects of using seaweed on animal health, and the potential for negative impacts on human health if the animals are consumed by humans. Some scientists have reported elevated levels of bromoform in milk after application of *Asparagopsis* supplements, however most of our interviewees stated that this was inconclusive (Wasson *et al.* 2022). According to reports by Fonterra, this has not emerged as a significant problem, but a standard might need to be developed for safe bromoform levels in milk (Macdonald 2023).
3. Measuring, reporting, and verifying (MRV) methane reduction is another complicated task. Specialized animal tests are required for measuring methane reduction, but many of these cannot be used for commercial verification, as they are inefficient. This has hindered developments in regulations and made it difficult for innovators to secure funding and sign commercial contracts. Certifications and standards would greatly advance the industry.
4. Supplying all 1.4 billion global cattle with seaweed is unfeasible because of supply chain challenges, and widespread adoption of methane mitigants in smallholder or subsistence agricultural systems is unlikely due to cost and other constraints (Vijn *et al*. 2020). Additionally, a proportion of cattle graze rather than being fed in feedlots, making it challenging to effectively incorporate this product into their diets.
5. Additionally, the seaweed industry must navigate intellectual property challenges and cultural barriers to acceptance (Purdom and Zou 2022). For example, FutureFeed currently holds the patent for *Asparagopsis* supplements, which poses a challenge for profitability, according to potential investors.
6. Several larger organizations have already invested in competitive products. This creates a barrier to adoption among some larger buyers, who have already invested in relationship-building and the promotion of competitive products.
7. Opposition to meat and dairy may be a challenge in the future, as people recognize the damaging environmental impact of livestock farming. However, it is unrealistic to expect an immediate end to industrial-scale animal production. Veganism is not culturally accepted in many countries. In addition, most current enteric emissions come from China, India, Brazil and other countries that are experiencing economic growth and where meat and milk consumption is expected to increase. Unfortunately, most technology companies are not yet located in these regions (Purdom and Zou 2022).
8. Price is highly important. According to our interviewees, the cost of the additive is the most important constraint. End-users are mostly expecting the inclusion of a methane additive in processed feeds or supplements to increase the price of that feed by no more than 5 percent (Hegarty *et al.* 2021a). It's important that seaweed products are competitive in terms of price per day.
9. High bromoform yield is desirable in the final seaweed biomass, but bromoform production in seaweed is heavily influenced by environmental growth conditions, such as temperature and geographic location, as well as sex and life cycle stage, which can be a challenge for producers.
10. The inherent difficulty with a halogenated compound such as bromoform, is that it can be lost to the environment through volatilization. Therefore, there is a need to develop innovative methods, with fewer steps, for the processing of intact, fresh biomass, which maximize the concentration and longer-term retention of bromoform.
11. In addition, discharged volatile halogenated chemicals can decrease atmospheric ozone, which may make it harder to approve seaweed feed additives. The FAO's new standards for the influence of feed on emissions take into account the impact of halogenated chemicals on the ozone layer.

Regulations

Regulations for anti-methanogenic supplements vary between countries. For instance, in the United States, government regulations pose barriers to the use of seaweed as a feed supplement. The FDA is currently revising policies for substances classified as drugs, and according to some stakeholders, there is ongoing debate over whether natural seaweed should be considered a drug. Although there has been more progress in Australia and New Zealand when it comes to anti-methanogenic seaweed supplements, regulations could still pose a significant challenge in Australasia, as New Zealand hasn't yet designed rules for methane inhibitors (Macdonald 2023). Interviewees emphasized that progress in Australasia will play a crucial role in convincing regulators in other regions, such as North America and Europe, to scale up the industry.

Market outlook

In 2021, stakeholders indicated that the global sales of methane-reducing feed amounted to just $30 million, and the market could reach $2 billion by 2030, growing at a CAGR of 57.4 percent (Nickel 2020). Seaweed startups have recently started to sell methane-reducing supplements commercially. And, based on our analysis of key drivers and dynamics, the projected seaweed-based market potential will reach $306 million by 2030. There are, however, some key potential deal-breaking challenges in this category in the long-term. These include competition from synthetic products, and availability of supply.

The high CAGR stems in part from the significant global interest, the scaling up of startups and demand for partnerships in this category. Over the past 24 months, FutureFeed has grown significantly and licensed its technology to multiple businesses globally (ASSA 2022). Another company, Sea Forest has spent the past two years scaling up production at its 1,800-hectare marine lease in Triabunna, Tasmania, where it has invested over $20 million in infrastructure. Sea Forest has tested its products with local dairy farmers, who give *Asparagopsis armata* supplements to their cows and sell the resulting milk to Fonterra, a dairy company from New Zealand. Meanwhile, in June 2021, CH4 Global made its first commercial sale of *Asparagopsis* cattle feed supplements in Australia, and in August 2021, the company announced a partnership with Clean Seas Seafoods, a producer of kingfish, to set up a seaweed nursery and production trials on land, using wastewater from the fish hatchery. The company has a five-year target of reaching 150 million cattle, 10 percent of the world total, on all six habitable continents (CH4 Global).

Overall, there is a lot of interest in this space from investors. A recent study by Hermans *et al*. (2023) showcased how the seaweed-based methane reduction industry ranked second in terms of overall investment into the seaweed space in 2022, trailing only behind biorefineries. This highlights the strong business case for these products, and the additional capital improves the odds that major challenges will be overcome.

Research, development and certification

One of the key questions facing the adoption of these products is their effect on productivity. To resolve this, FutureFeed has focused on conducting large-scale trials to demonstrate the benefits of *Asparagopsis* supplements on cattle productivity (Community acceptance of low-methane meat 2022). Productivity gains and improved feed conversion ratios are major drivers of purchasing decisions by farmers, as they can reduce costs. This will be an important development for the market.

According to our interviewees, seaweed cultivators are quickly advancing their technology to achieve large-scale production. For instance, producing significant quantities of *Asparagopsis* has been a challenge in the past, because of difficulties in inducing spore release in aquaculture facilities. However, companies have now discovered ways to initiate this, allowing spores to be seeded and attached to aquaculture lines. These developments, coupled with advancements in breeding and selection techniques, are leading to higher quality seaweed that requires less biomass to achieve the same methane reduction.

As of January 2023, a program is being developed by FutureFeed to certify the production system for *Asparagopsis*. This will be a third-party verification program for claims and carbon accounting. It will ensure traceability of *Asparagopsis* products in the market and assist producers in accurately calculating methane reduction. This program aims to establish a repeatable and high-quality production system for *Asparagopsis*, enabling confidence in methane reduction calculations. It also seeks to provide consumers with confidence in the methane emission reduction claims made on red meat, dairy and wool products. This will aid in improving attitudes toward the products, and convincing purchasers over the next 24 months.

Another important aspect is the development of carbon credit verification processes, which can be used to incentivize farmers to use seaweed as a feed supplement. Carbon credit markets are still being developed for anti-methanogenic products, but stakeholders reiterated that this market will move quickly in the next 18 months to help valorize the environmental benefits provided by these products. Mootral already has a credit scheme certified by VERRA. Companies that manufacture methane-reducing feed additives have filed proposals to earn carbon credits for their products' use. In Australia, these companies have applied to the Emissions Reduction Fund To access Australian Carbon Credit Units (ACCUs). Our stakeholder interviews indicated that this space should be developing rapidly over the next 24 months, aided potentially by regulatory pressure from governments and tax-payer-funded subsidies for farmers buying the product.

Additional technology in development / requirements

1. When it comes to land-based farming, several companies are showing rapid scaleup. CH4 Global is now building an EcoPark production facility in New Zealand that will allow for the large-scale commercial production of *Asparagopsis*. The new facility will help guarantee controlled and consistent production of the seaweed as it expands its commercial supply to the Australian and New Zealand markets. Meanwhile, Symbrosia has plans to develop a facility that will increase production by a factor of 1,000 in Hawaii.
2. Researchers are hoping to produce seaweeds with higher yields of bromoform, which will mean feeding smaller amounts of supplement to cattle. This is important, as stakeholders indicate that production required to service the world with anti-methanogenic seaweed supplements like *Asparagopsis* may be unfeasible. Stakeholders have highlighted the importance of developing effective methods for screening more diverse species that may mitigate enteric methane emissions. Collaboration is necessary to build approaches in this regard (Vijn *et al*. 2020).

Target geographies and initial markets

There is potential for methane-reducing supplements to be produced all over the globe, particularly as inland facilities currently provide higher breeding and cultivation success rates. However, when considering growing in the ocean, to comply with local regulations, it is important to identify and select seaweeds that naturally grow in the area or pose minimal risk to the environment.

When it comes to investing in the emerging anti-methanogenic seaweed industry, some of the most promising short-term markets include Australia and New Zealand, where the sector is currently most developed. When choosing locations for production facilities, it is important to consider the availability of feedlot cattle as a potential market for the seaweed, and if the product can be easily shipped dry and imported.

4.5. Nutraceuticals

Key highlights

Nutraceuticals

Some niche applications of seaweed-based nutraceuticals already exist, but no data on market size are available.

Global nutraceutical market: $450 billion in 2022.

Projected market growth: 7.5 percent CAGR between 2022 and 2030.

Projected seaweed nutraceutical market potential: $3.9 billion by 2030.

Primary drivers

- Rising levels of several communicable diseases, rising healthcare costs, aging populations, and increased consumer awareness.

Main challenges

- Quality and certification of nutrition claims require expensive and lengthy clinical trials.
- Quality and consistency of seaweed supply, combined with the complexity and expense in deriving the necessary compounds to create targeted and measurable nutraceutical products.

Outlook: One of the most promising high-value opportunities for seaweed-based ingredients. However, key challenges make the exact timeline for wide commercial adoption unclear. It is reported that there are many clinical trials under way, but interviewees report that there is a need for much more clinical work to provide safe products that deliver the claimed health and nutrition benefits. As clinical trials require at least two years and often longer, this could reduce the speed of commercialization.

Introduction

Nutraceuticals are dietary supplements that may provide nutritional support but are considered food-based. Although nutraceuticals may contain necessary, and even therapeutic, ingredients – such as vitamins and essential trace elements – they are not drugs and fall into a different regulatory category. There is no unified accepted definition for the term “nutraceuticals,” which was originally coined in 1989 by Stephen De Felice (Santini and Novellino 2017). Nutraceuticals are often aimed at one particular aspect of health, such as cardiovascular health, brain health, or immune support.

Seaweed’s value proposition

Within these nutraceutical subcategories, seaweeds are becoming a particularly sought-after ingredient, thanks to their rich mineral and bioactive compound content (Ganesan *et al*. 2019). Seaweeds may provide a vegetable source of B12 (Watanabe *et al*. 2014). Trace element contents in edible seaweeds makes them attractive for inclusion in the diet

(Lozano Muñoz and Díaz 2022). Studies have shown that incorporating seaweed into one's diet can lead to reduced inflammation, improved overall well-being, and various other health benefits (Lozano Muñoz and Díaz 2022; Olsthoorn *et al*. 2021; Shannon and Abu-Ghannam 2019).

Brown seaweeds used include *Fucus vesiculosus, A. nodosum, Alaria* sp., *Laminaria* spp., *Undaria pinnatifida,* and *Cladosiphon* sp. Additional farmed resources – notably *Macrocystis* sp. And *Laminaria digitata* – are being developed (Purcell-Meyerink *et al*. 2021).

The green seaweed *Ulva* spp. Can be cultivated and has an excellent nutrient and mineral profile, making it well suited for inclusion in functional foods. Red seaweeds, such as dulse (*Palmyra palmata*), also have excellent nutritional profiles. Although they have little presence in the dietary supplement market, perhaps because of their use as food products, their inclusion in functional foods is increasing (Pacheco *et al*. 2022).

In Asia, seaweeds are commonly included both in the diet and in therapeutics. In traditional Chinese medicine, 171 species of medicinal algae are listed in the *Chinese Marine Materia Medica* (CMMM) (Fu *et al.* 2016). The use of seaweeds in traditional medicine is outside the scope of nutraceuticals but illustrates their remarkable potential (Yang 2016).

Beyond these sectors, nutraceuticals derived from seaweed and seaweed extracts can provide a wide range of benefits. For example, antiviral (Geetha Bai and Tuvikene 2021) and anticancer activities have also been highlighted by researchers (Zayed *et al*. 2022). In Japan, many consumers of fucoidan nutraceuticals are cancer patients, and this is an accepted practice. A considerable body of preclinical research exists into these effects. In the last decade, a small number of clinical trials have been carried out to determine the safety and efficacy of supplements for cancer patients. However, to date, the effects of fucoidan on clinical outcomes in metastatic or recurrent cancer patients have been inconsistent (Wu *et al*. 2022), and more studies are needed. In general, there is a need for more clinical studies with dietary seaweed and seaweed extract nutraceuticals to improve consumer and clinical decisions. Since dietary supplements are not drugs, it is very important that no claims are attached to any functional activity unless they are approved claims.

An overview of seaweed-based compounds relevant to the nutraceutical market is presented in Table 14.

TABLE 14: Typical ingredients used in nutraceuticals from different types of seaweed

	Brown (Phaeophyta)	Red (Rhodophyta)	Green (Chlorophyta)
Polysaccharides	Fucoidan	Carrageenan	Ulvan pure
	Laminarin	Porphyran	Ulvan glycoprotein
	Fiber	Agar	
Carotenoids	Fucoxanthin	Zeaxanthin	Siphonaxanthin
Polyphenols	Polyphloroglucinols		
Proteins	Protein/amino acids	Protein/amino acids	Protein/amino acids

Alginates are most commonly used in food and pharmaceuticals and less relevant in their application in nutraceuticals. However, oligo alginates, created by enzymatic and chemical hydrolysis, are emerging as potential immune support nutraceuticals (Bi *et al*. 2022).

Fucoidan already has established itself in the nutraceutical market. It is a class of sulfated compounds containing a large amount of polymeric fucose, with each brown seaweed yielding a slightly different type. It is important to recognize these structural and functional differences. Fucoidans have a range of bioactivity – including inflammation blocking, antiviral effects, and anticancer effects (Fitton 2019; Zayed and Ulber 2019).

Laminarin is a beta-glucan-branched glucose storage polysaccharide found in brown seaweeds, typically in *Laminaria* species. Laminarin has favorable microbiome-modulating properties (Shannon *et al*. 2021), and a similar range of bioactivities to ulvan and fucoidan. It is an emerging market that may grow in size as biorefineries start production.

Fucoxanthin is a carotenoid found in brown seaweeds. It has been found to have effects on fat metabolism by increasing the expression of uncoupling protein, and has been assessed clinically (Abidov *et al*. 2010). A small market has developed for the sale of this product in the dietary supplement sector aimed at weight loss. The yield of fucoxanthin from seaweeds is very low (<<0.5 percent wet weight) and requires specialty extraction techniques that add to the production costs. Recent studies have identified that only two out of ten supplements actually contained the stated amount of fucoxanthin (Hossain MF 2019). New developments in production may assist in more reliable supplies (Iha and Fujii 2021).

Ulvans, like fucoidans, vary in composition according to their source. In general, they contain sulfated polymeric xylose, rhamnose, galactose and uronic acid, with branched structures. When derived from a controlled culture source, a reproducible product can be obtained (Winberg *et al*. 2014). Recent clinical studies indicate that dietary ulvan has anti-inflammatory effects (Roach *et al.* 2022). The market for ulvans is emerging, and has considerable potential in nutraceutical sectors (Liu *et al*. 2022).

Amino acid profiles of seaweed proteins are unusually complete, and may contain the rare amino acid taurine, which has bioactivity suited to nutraceutical use (Duszka 2022). Complementary essential amino acid profiles in different seaweeds could be mixed to form protein blends that are nutritionally on par with animal products such as milk and whey (Reynolds *et al*. 2022). Although seaweed-derived peptides and proteins are not currently on the market, upcoming biorefinery approaches may begin to provide adequate supplies (Černá 2011).

Processing

Seaweed nutraceutical products can be made from whole, dried, and milled kelp, or from seaweed extracts. Each type of seaweed or seaweed extract has unique processing requirements. Whole seaweed may require milling to specification. The high salt content and tough fibers require durable milling equipment.

When preparing extracts, generally speaking, water soluble components in any type of seaweed can be extracted using traditional batch processing by controlling temperature and pH. Salts can be removed by filtration methods, and further processing concentrates the extract prior to drying or inclusion in the final product. More recent processing innovations include the use of ultrasound, enzymes, and microwaves (Fitton 2019).

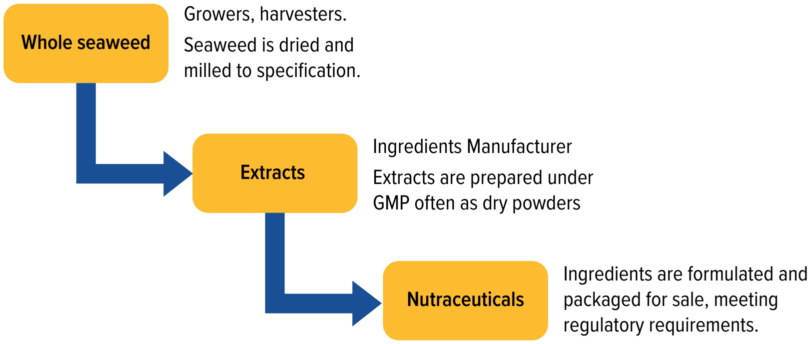
The water-soluble polysaccharides – fucoidans (from brown seaweed) and ulvans (from green seaweed) – are unique to their source material. They may co-extract with other components, which may be acceptable for some nutraceutical purposes (Fitton 2019). They vary in size, presenting a range of molecular weight compounds with similar composition. Careful control of source materials and processes is required for product consistency.

Some fucoidan manufacturers use an ethanol precipitation method to create a high-quality fucoidan product. In some cases, the use of ethanol may be connected to other aspects of the business – such as fermentation to ethanol from biomass, which can make this a cost-effective approach.

More recently, biorefinery approaches by emerging manufacturers mean that multiple products can be created from a single seaweed biomass. In the case of large kelps, this can include alginates, fucoidan, laminarin and celluloses. A recent paper describes a typical approach for generating multiple product streams from *A. esculenta* and *S. latissima* (Birgersson *et al*. 2022).

Recently, new innovations to increase the yield and extraction of fucoxanthin (brown seaweed) and siphonaxanthin (green seaweed) have also been described (Iha and Fujii 2021).

FIGURE 15: Process flow diagram for the development of nutraceutical products



The nutraceutical value chain usually consists of several entities. The sector is generally divided into three:

A) Producers of seaweed.
B) Ingredient manufacturers of seaweed extracts.
C) Nutraceutical manufacturers who create capsules, gels, and drinks that include either whole seaweeds or “bioactive” seaweed extracts.

The final products are then sold by brick-and-mortar retailers or online (GM Insights 2022). An additional category is the multilevel marketing of nutraceuticals. There are several of these businesses that include seaweed extracts in either drink, gel, or capsule formats. Two additional retail categories are in “practitioner-only” brands and pet nutraceuticals (see chapter 4.3).

Ingredient manufacturers source their raw materials from the global seaweed market. Continuity and integrity of supply are critical, and therefore some businesses have strong links to the growers. Selling ingredients into the nutraceutical market is a business-to-business (B2B) operation and requires a unique focus on the nutraceutical companies as the key customers. Adequate shelf life, purity, consistency, and appropriate certifications may all be required by the nutraceutical customer. Some ingredient manufacturers use distributors, which introduces an additional step into the value chain.

Although less common, some businesses are fully vertically integrated: they grow their own seaweed, produce extracts, brand nutraceuticals, and sell to the end customer. Although full vertical integration is effective on a smaller scale, as a business grows it may also start selling in the B2B space. This may occur when the business begins to manufacture larger volumes of seaweed or seaweed extract.

The volumes required for batch processing are different for each manufacturer. One seaweed-based nutraceutical manufacturer uses one ton per batch, where a yield of the target extract would typically be 5–10 percent wet weight.

Market overview

The nutraceuticals market covers a wide range of products, including functional foods such as fortified cereals, dairy, snacks and beverages such as energy and sports drinks, in addition to the dietary supplement category. Dietary supplements are most commonly packaged as capsules – although liquids, powders, gels, and gummies are also common – and may contain vitamins, botanicals (including seaweed), minerals, oils from botanical and fish sources, enzymes, and probiotics. Additional blurred boundary market sectors include cosmeceuticals and nutricosmetics, although these may be counted as nutraceuticals (Santini *et al*. 2023).

TABLE 15: Examples of current nutraceutical market sectors

Sector	Size of whole sector	Seaweed bioactivity example
Bone and joint health	$2.16 billion in 2021 (Polaris Market Research 2022)	Dietary correlation (Lim *et al*. 2015; Jeong *et al*. 2019)
Gut health	$44.4 billion in 2022 (Grandview Research 2022)	Microbiome support, reduces inflammation (Olsthoorn *et al.* 2021)
Immune support	$18.22 billion in 2020 (Fortune Business Insights 2022c)	Supports immune function (Zayed *et al*. 2022)
Sports, energy and weight management	$130 billion in 2021 (GM Insights 2022)	Assists weight management (Hossain 2019; Yang *et al.* 2022)

In 2019, the Asia-Pacific region accounted for 31 percent of the market. Japan alone accounted for about a fifth of the Asia-Pacific market. In 2012, China ranked fourth in global sales of dietary supplements, behind the United States, Japan and Europe, with sales amounting to $15.8 billion (Yang 2016). China provides 65 percent of herbal raw materials for the manufacture of traditional Chinese medicine, a category that overlaps with nutraceuticals (Yang 2016). The Indian market for all nutraceuticals was predicted to reach $8.5 billion by 2022 (Business Standard 2017).

In Europe, Germany accounts for the largest market share, followed by the UK and France. Central and Latin America show increasing demand for nutraceuticals, with the Brazilian market worth $13.25 billion in 2021. In the next decade, above-average growth is expected in China, India, and Brazil (Chopra *et al*. 2022).

In 2021 the global market size was estimated at approximately $450 billion, with an estimated CAGR of at least 7.5 percent. In 2020 the global dietary supplements segment (considered a subsegment of nutraceuticals) in the US, Canada, Japan, China, and Europe had a combined market size of $41.4 billion (Globe Newswire 2022).

Other estimates are somewhat higher, with forecasts that the value of dietary supplements will grow from $71.81 billion in 2021 to $128.64 billion in 2028, at a CAGR of 8.68 percent (Fortune Business Insights, 2022b). Despite variations in market size and CAGR estimates, the overall consensus is that the market is large and growing (Santini *et al.* 2023). In 2021 the approximate market share of the different nutraceutical sectors was functional beverages 32 percent, functional foods 40 percent, and dietary supplements 28 percent (GM Insights 2022).

Notably, E-commerce is a growing category within the retailing of nutraceuticals. In 2021, it was estimated to be worth $116 billion, out of a total nutraceutical retail market of $396 billion (GM Insights 2022).

Each of the trends highlighted in Table 15 may grow at different rates. For example, it was recently estimated that the global "brain health" supplement category will grow to nearly $5.8 billion by 2023 (Roe and Venkataraman 2021).

The higher-value seaweed market segments are for fucoidan – an extract of brown macroalgae. The global B2B fucoidan market size was estimated at $36.04 million in 2021 and is projected to reach $45.57 million by 2028, at a CAGR of 3.41 percent (MarketWatch 2022). As a comparison, this is smaller than the global medicinal mushroom market, which was projected to increase by $13.88 billion between 2018 and 2022, but larger than that of mushroom-derived lentinan, at $10 million in 2020 (Niego *et al*. 2021).

Manufacturers of seaweed ingredients, and nutraceutical manufacturers are maintaining production and increasing capacity and sales. The Japanese market is saturated with seaweed as a food, but has space for the development of the seaweed extract market. The fucoidan market in Japan is almost entirely cancer patients. The size of the retail (consumer products) fucoidan market in Japan was over 15 billion yen ($116 million) in 2018 (Nagasue 2018; Koe 2018). By contrast, markets outside of Asia require considerable investment in consumer awareness.

Both established manufacturers and key opinion leaders feel that increased consumer awareness and increased investment in clinical trials are necessary to grow the market effectively. The cost of clinical trials can be prohibitive, meaning that some ingredient manufacturers are reluctant to invest in clinical R&D.

New innovators are developing extracts, including bioactive sulfated polysaccharides (fucoidan, laminarin and ulvans), as well as carotenoid products such as fucoxanthin. There is often a biorefinery approach to developing these extracts, currently mainly at the lab scale.

Market space for these compounds is not yet fully developed, but there is considerable consumer demand in the target sectors for the anti-inflammatory, immune support, cardiovascular health, joint health, and gut health of these products.

Innovators are also investing in clinical trials after initial scientific studies. These trials help to build confidence in the efficacy of the product and meet the needs of the dynamic nutraceutical market (Santini *et al.* 2023).

A key opinion leader in complementary medicines noted that more clinical work was needed in the nutraceutical industry, along with clinician and consumer education.

Market dynamics

Drivers

COVID-19 had a stimulating effect on the global nutraceutical markets, with consumers seeking additional protection from viral infections by using products that purport to have immune-boosting effects (Lordan 2021). In the US, during the first wave of the pandemic in the six weeks preceding 5 April 2020, there was a 44 percent increase in sales of these products compared to the same period in the previous year. In March 2020, vitamin sales increased by 63 percent in the UK and by 40 to 60 percent in France versus the same period in the previous year (Lordan 2021). Seaweed extracts are especially attractive because of their bioactivity profile (Shannon and Abu-Ghannam 2019). The consumption of seaweed extracts as functional foods or dietary supplements is expected to markedly rise in the future, partly as a result of the increase in the total nutraceuticals market, and partly because of their greater market presence.

Markets for nutraceuticals extracted from green macroalgae (phylum Chlorophyta), brown macroalgae (phylum Phaeophyta), and red macroalgae (phylum Rhodophyta) are emerging. Although seaweed proteins and peptides have not yet emerged in the nutraceutical market, they are likely to do so when biorefinery-type production increases. Biorefinery systems optimize the extraction of all components and may be able to capture previously wasted protein and peptide biomass.

The nutraceutical market displays several health target trends, some of which are listed below. Seaweed extracts have the potential to increase market share in most of these sectors. The trends likely to drive market growth include the rise in the prevalence of several communicable diseases, rising healthcare costs, aging populations, and increased consumer awareness (Chopra *et al.* 2022), as well as the COVID-19 pandemic. The market sectors include immune-support, anti-inflammation, anti-aging, beauty from within, bone and joint health, gut and digestive health, sports, energy and weight management.

The market saturation for products is highly variable: at one extreme is Japan, which is a naturally educated and partially saturated market, and at the other is the US, where a nascent market requires consumer education and exposure.

Competition

Nutraceuticals containing seaweeds and seaweed extracts are unlikely to replace other bioactive products but will add to the set of consumer-controlled dietary solutions. They will also become available for inclusion in formulated products in which ingredients have complementary activity. Entirely new areas of consumer products can be created by intelligent formulation, meeting trends in this dynamic market space.

Nutraceutical ingredients are numerous and have a wide range of pricing. Some common nutraceutical ingredients with well-established mature markets include omega-3 lipids and medicinal mushrooms (Chopra *et al.* 2022; Niego *et al*. 2021). The global market for omega-3 products was $730 million in 2022 (Market Reports World 2023). One new and upcoming nutraceutical ingredient is cannabidiol (CBD), with a market value of $9.67 million in 2021 and a remarkable CAGR of 40 percent (Research and Markets 2020), although this ingredient may still have to overcome regulatory barriers in some countries.

In high-quality clinical trials, some seaweeds and seaweed extracts have demonstrated benefits to chronic health conditions. For this reason, seaweed extracts may be able to assist in the control of mild inflammation and reduce reliance on, for example, drug products for conditions affecting joints, the digestive tract, and skin. Since nutraceuticals are not designed to replace drugs, this is a consumer-controlled dietary approach to health management and is attractive to formulators.

One interviewee, a clinical opinion leader, explained that evidence from high-quality, double-blind, randomized, placebo-controlled, clinical trials was valid, regardless of whether it was for a drug or for a natural product.

The value chain from ingredient manufacturer to nutraceutical manufacturer creates persistent challenges. It is sometimes believed that the US consumer will pay approximately $1 per day for a nutraceutical. This creates a perceived price ceiling for ingredients, which further need to be formulated, packaged, and marketed. Because of this, the ingredient supplier may not invest in clinical trials at appropriate dosages, or an end product might not contain an effective dose of one or more core ingredients. A major opinion leader felt that the reluctance of manufacturers to go above a perceived price ceiling of a proposed product was a barrier to success. “A much better model is to develop effective agents and then make the market. If a supplement makes a significant difference to someone’s health, they will pay for it, and the market will develop,” they argued.

Seaweed extracts vary greatly in price. Fucoidan pricing in the B2B space may range from $300 to more than $1000 per kg, depending on source, purity, certifications, and intended use.

Challenges

1. Availability of consistent supply

For ingredient manufacturers, a main barrier to entry is a reliable and safe source of seaweed or seaweed extract. Variations in available harvest volumes due to environmental conditions need to be factored into any business plan. Batch consistency and reliable suppliers are also critical for the nutraceutical manufacturer and retailer. Mitigating the risk of inconsistent supply requires alternative suppliers and storage of enough stock.

2. Drying cost

An inhibitor to the use of whole seaweed biomass includes the costs of drying, which is influenced by the level of salt content in the biomass. This varies according to the type of seaweed and the geographical location. Since fresh seaweed usually contains 90 percent water by weight, the logistics and costs of drying can be considerable. Dried, whole seaweed is generally very stable, with a high salt content that assists in preservation. If manufacturing processes are in place locally, wet seaweed can be used for extraction directly after harvest, eliminating this step and lowering production costs.

3. Yield of target extract

The yields of the brown seaweed extracts fucoidan and laminarin are usually far less than 10 percent wet weight. Newer biorefinery processing techniques mean that manufacturers will be able to create multiple product streams from one biomass, making production more economically viable.

4. Safety hazards

Additionally, there may be chemical or biological food safety hazards present in seaweeds (FAO and WHO 2022). Chemical hazards include heavy metals (lead, arsenic, mercury and cadmium) and high or unknown iodine levels. (See “A note on iodine and dietary supplements.”) Pollutants such as radionuclides, pesticide residues, and persistent organic pollutants are also potential hazards. Heavy metals and other chemical contaminants must be absent for seaweed to be used in nutraceuticals (FAO and WHO 2022), or for input into manufacturing. Although many countries have guidelines for upper tolerable limits, an international standard is vitally needed.

Biological hazards include bacterial and viral contamination. A very small number of seaweeds naturally contain compounds that cannot be included in nutraceuticals, such as kainic acid (Sakai *et al*. 2005) found in *Digenea simplex*, and bromoform in *Asparagopsis* spp. (National Library of Medicine 2022).

5. Compliance costs

Ingredient manufacturers need to meet regulatory standards. The Hazard Analysis and Critical Control Points (HACCP) system is a step-by-step approach to the identification, evaluation, and prevention of biological, chemical, and physical hazards from entering the food production process based a set of management principles, guidelines, and tools that cover all stages of food production, from harvest to consumption. Backed by the FDA and (since 1994) the International HACCP Alliance, it is a prevention-focused system aimed at keeping problems from occurring in the first place, rather than detecting and correcting them after the fact. Businesses in all segments of the food industry can use the HACCP system to achieve reliable safety throughout all production processes. The FAO offers an excellent resource to assist those in developing nations (FAO 2022a).

In many countries, whole seaweeds are regularly consumed and have achieved regulatory approval as foods – for example, as “not novel” foods in Europe. Nutraceutical manufacturers may require a seaweed extract to be generally recognized as safe (GRAS) in the US, or classified in the EU list of novel foods in accordance with Regulation (EU) 2015/2283. Regulatory consultants are available to help manufacturers determine how to proceed, according to where the nutraceutical is to be marketed.

6. Capital requirements

Vertically-integrated operations may require significant capital to assist in scaling production and also need to account for variations in production. For startups either in the manufacturing space or in the nutraceutical space, capital is a key entry barrier. Government grants to establish processing and investment capital are often used by startups.

Value-adding by the primary producer – by drying, milling, or crude extraction – is of great value to the ingredient manufacturer because some of the steps in their processing can then be removed.

7. Consumer awareness and adoption

Another barrier is the lack of consumer awareness of the benefits of seaweed extracts, and a need for clinical trials. As a major opinion leader noted, “Asian markets have a longer and richer history with seaweed products. Barriers to usage are lower than Europe and Americas as the education is further ahead.”

8. Regulatory barriers

Supplements may be regulated very differently from country to country (Rojas *et al*. 2022). It is sometimes difficult to determine how a supplement should or could be classified, for example, as a food or a drug (Visioli 2022), and it is important to seek guidance in each jurisdiction.

In the US, the Dietary Supplement Health and Education Act (DSHEA) has created a regulatory framework for dietary supplements (Burdock 2000). DSHEA mandates safety and labeling of products prior to marketing. Although the manufacturer does not have to provide evidence to the FDA, they must establish good manufacturing practices. In the US, claims may be made about a dietary supplement, within guidelines. For example, no statements can be made that imply the supplement has an effect on a disease. However, a "structure-function" claim can be made, such as "promotes joint health" or "supports the immune system."

In Europe, food supplements are defined as concentrated sources of nutrients (that is, minerals and vitamins) or other substances with a nutritional or physiological effect that are marketed in "dose" form. They can include vitamins, minerals, amino acids, essential fatty acids, fiber, and various plant and herbal extracts. Food supplements are intended to correct nutritional deficiencies, maintain an adequate intake of certain nutrients, or support specific physiological functions. They are not medicinal products and so cannot exert a pharmacological, immunological, or metabolic action. Therefore their use is not intended to treat or prevent diseases in humans or to modify physiological functions (European Food Safety Authority n.d.).

Worldwide, there is considerable discussion around the regulation of nutraceuticals (Visioli 2022) and the regulatory landscape varies internationally.

TABLE 16: Regulatory bodies for nutraceuticals

Country	Regulatory body	Details
US	Food and Drug Administration	Federal Food, Drug and Cosmetic (FD&C) Act, as amended by DSHEA and FDA regulations.
Canada	Natural and Non-prescription Health Products Directorate (NNHPD)	Natural health products require a product license. Sites that manufacture, package, label, and import must have a site license.
EU	European Food Safety Authority	Food supplements are intended to correct nutritional deficiencies, maintain an *adequate intake* of certain nutrients, or support specific physiological functions.
Australia	Therapeutic Goods Administration (TGA)	Medicinal products containing herbs, vitamins, minerals, and/or nutritional supplements are referred to as "complementary medicines" and are regulated as medicines under the Therapeutic Goods Act 1989.
Russia	Rospotrebnadzor	Food supplements are regulated by the Federal Service for Surveillance on Consumer Rights and are implemented by Rospotrebnadzor.
China	National Medical Products Administration	Complex process of regulation. Traditional Chinese medicine also includes seaweeds.
India	FSSAI	Food Safety and Standards (Health Supplements, Nutraceuticals, Food for Special Dietary Use, Food for Special Medical Purpose, Functional Food and Novel Food) Regulations 2016.

BOX 5: A NOTE ON IODINE AND DIETARY SUPPLEMENTS

Iodine is an essential micronutrient required for normal brain and musculoskeletal development. Sufficient iodine intake is particularly important for pregnant women and for children. The tolerable upper intake level (UL) is 600 µg/day for adults and 200 µg/day for children (National Institutes of Health 2022).

Low levels of iodine in the soil may lead to diets that are low in iodine. Iodine-containing supplements may contribute substantially to intake in Western diets (Newman *et al*. 2019). Recent efforts have been made to create databases containing the iodine content of major dietary contributors, including supplements (Ershow *et al*. 2018).

Iodine is a component of all seaweeds, with the highest levels in large brown kelps (Teas *et al.* 2004).

A recent study on seaweed for food purposes available in Europe identified iodine levels exceeding the upper threshold in a variety of seaweed food products (Aakre *et al*. 2021). However, as seaweeds are rarely eaten daily in Europe, this may not represent a public health issue. It is perhaps more pertinent to carefully consider iodine levels in seaweed supplements, as these are designed for daily intake. Claims can be made for iodine as a component in nutraceuticals. For example in the EU, one claim that can be made is that “iodine contributes to normal cognitive function” (EFSA Panel on Dietetic Products and Allergies 2010).

Ingredient manufacturers can take several years to reach the market, as they need to build processing plants, comply with local regulatory conditions for manufacturing, establish supply lines, and develop customer relationships. Manufacturers need to implement Good Manufacturing Practice (GMP)/HACCP; additional certifications – such as organic, halal, kosher, and GMO-free – may also be desirable in certain markets.

Ingredient manufacturers are often the entities that carry out their own product R&D. The market value of the raw material rises with validated ingredient content and evidence of its proposed activity when incorporated into a nutraceutical. Preclinical and clinical trials may take two or more years from conception to publication. Preclinical work may involve assessing the effects of an extract in cell culture or an enzyme assay, for example. Clinical trials are not necessarily required for commercialization but greatly assist in increasing a nutraceutical ingredient’s value in the market. A recent publication noted that “advances in nutraceutical-based preventive and proactive approaches require reliable clinical data substantiating their efficacy” (Santini *et al*. 2023).

Some clinicians may be concerned that patients who are already taking pharmaceuticals may experience adverse effects from self-administered nutraceuticals. Interaction studies are uncommon but, in particular market sectors, they can be useful to ensure safety and establish confidence.

TABLE 17: Examples of different types of studies of seaweed

Type of study	Seaweed-based ingredient	Notes	Reference
Pilot study	Seaweed in bread	Effect of seaweed-enriched bread on carbohydrate digestion.	(Wilcox *et al*. 2021)
Interaction study	Fucoidan	Study on the pharmacokinetics of letrozole and tamoxifen.	(Tocaciu *et al.* 2018)

(Table Continued)

TABLE 17: ***Continued***

Type of study	Seaweed-based ingredient	Notes	Reference
Randomized, placebo-controlled trial (RCT)	Sulfated polysaccharides	Improved plasma lipids, anti-inflammatory activity, and microbiome shifts in overweight participants.	(Roach *et al*. 2022)
Epidemiological study	Total diet, including seaweed	Prevalence of osteoporosis in Korean postmenopausal women according to nutrient and food group intake.	(Lim *et al*. 2015)
In vivo study	*Eklonia radiata*	Gut health benefits of *E. radiata* and its polysaccharides *in vivo.*	(Charoensiddhi *et al*. 2017)

In summary, clinical trials can be carried out by research-based universities or contract research organizations. To yield meaningful results, the trial protocol, endpoints, participants, and compliance must all be carefully considered (Martínez-López *et al*. 2022; Staudacher *et al*. 2022). Trials must first be assessed by ethics committees and registered with the appropriate authorities. Pilot trials are sometimes required to guide design. Double-blind, randomized, placebo-controlled trials (RCTs) are statistically-powered studies that produce the highest-quality data. After the trial has been conducted, the data needs to be analyzed before the results are published. Although trial design can vary greatly, it can be helpful to consider three broadly applicable phases that are used in pharmaceutical research.

FIGURE 16: The three phases of a typical pharmaceutical trial

Phase 1	Safety and efficacy; may include placebo; 20–80 participants
Phase 2	Efficacy and dosing (includes safety); 100+ participants; must be statistically powered for the primary endpoints
Phase 3	Safety, efficacy and dosing; 1000+ participants

Key measured outcomes are referred to as primary endpoints. These can be either biological, such as a serum and urine biomarkers; physical markers, such as assessing the range of motion of a joint; and/or a participant assessment taken on a validated questionnaire on factors such as quality of life. Although nutraceuticals are not drugs, it is still wise to include safety assessments within trial designs.

Other types of trial design include longitudinal studies (carried out over many years), interaction studies (to examine interactions with drugs), or post-market studies. Depending on its size and complexity, a full statistically-powered trial may take more than two years from conception to completion, and cost well in excess of $1 million (Cobain 2018).

Market outlook

There is a clear momentum toward the development of innovative nutraceuticals that improve consumer health. The global nutraceutical market is projected to grow at a CAGR of approximately 7.5 percent per year. Seaweed-derived nutraceuticals could capture a $3.9 billion market by 2030. However, significant challenges make the exact timeline for wide commercial adoption unclear. Many clinical trials are reported to be under way, but interviewees stated that there is a need for much more clinical work to provide safe products that deliver their claimed health and nutrition benefits.

Nutraceutical manufacturers with existing distribution and sales networks may take up new supplies of seaweed extracts and place them on the market within a year or two, subject to regulatory requirements and normal product development processes, such as formulation-stability testing and packaging. All of these activities take time and resources but are important to customer safety.

Whole, dried seaweed needs to be available at a low cost to make extraction of the relevant compounds viable. Interviewed manufacturers of extracts in Japan, Korea, Scotland, and Australia maintained that the price point for their input materials was already viable.

Several interviewees in the ingredient production sector were expecting to increase their business. An established company with an annual turnover of just? Under $20 million expects to double its output by 2028. Several new entrants into the market with turnover of under $1 million were expecting to increase output several fold.

4.6. Alternative proteins

Key highlights

Alternative proteins

There are examples of seaweed-based meat and seafood alternatives, but no data on market size are available.

Global alternative protein market: $10.2 billion in 2022.

Projected market growth: 36 percent CAGR between 2022 and 2030.

Projected seaweed-based, alternative-protein, market potential: $448 million in 2030.

Primary drivers

- Increasing interest in non-animal-derived food protein products.
- Increasing awareness from consumers and product developers about multi-functional properties of seaweeds, balanced profile of essential amino acids and potential food supply chain sustainability improvements.

Main challenges

- Competition from other, cheaper biomass which has higher protein concentrations.
- Technical challenges with protein extraction.
- Availability of sufficient seaweed volumes with consistent protein contents.

Potential "deal-breaker" challenge

- Cost of production of high-protein concentrates.

Outlook: The development of seaweed-derived proteins as white-labeled ingredients to compete with other alternative proteins, such as pea or soy, is being explored by a number of companies. It was also reported that protein extracts from seaweed would only be part of a wider biorefinery approach, and may only gain competitive advantage if some other function – such as binding or gelling – can be provided in a single-source ingredient.

Introduction

Per capita meat consumption around the world is at the highest level it has ever been. According to some estimates, humans consume approximately 350 million tons of meat every year, and global meat production is projected to double by 2050 (Good Food Institute 2022; Hooper and Dace 2021). This has raised questions about the ability to supply that ravenous demand. Without improvements to food supply chains, there may not be enough land to produce enough animal protein for the growing global population.

Scaling up animal protein production could also have major environmental impacts because livestock production methods are significant drivers of GHG emissions, deforestation, and the loss of biodiversity. Compared to animal-derived meat, making meat from plants, insects, algae, or cultivated cells can reduce land and water consumption, GHG emissions, and pollution. There are also fears that the intensive methods used today in animal farming are leading to a rise in antibiotic resistance and an increase in the likelihood of pandemics (Hooper and Dace 2021).

Alternative proteins are proteins for human consumption that are not sourced from animals (for example, plant-based or food technology-based alternatives). They are widely seen as potential solutions to the problems associated with livestock production. They can be sourced from plants (for example, grains, legumes and nuts), fungi, algae, or insects, or cultured – that is, lab-grown (University of Melbourne n.d.). These sources can all be delivered in various forms, from whole biomass to milled flours and more processed extracts such as isolates and concentrates – each with a different level of protein concentration.

For example, soybeans are a common source of alternative-protein products. They can be turned into soybean meal by extracting the oil from soybean flakes. Soy flour is made by grinding soybean flakes into a fine powder. From there, the flour can be de-fatted to create soy protein concentrate, which is about 70 percent soy protein. Further removal of non-protein components – for example, fibers – from soy protein concentrate creates a highly refined, purified form of soy protein called soy protein isolate, which has a minimum protein content of 90 percent, on a moisture-free basis.

Seaweed's value proposition

Seaweeds are seen as potential alternative-protein sources. Macroalgae have been eaten for thousands of years and contain up to 47 percent protein by dry weight, although this varies greatly among species. Brown seaweeds typically have a lower protein content, compared to the moderate/high protein content found in green and red seaweeds (Fleurence *et al.* 2018) (see Table 18).

TABLE 18: Protein content of several seaweed species alternative proteins

Seaweed genus and species	Protein content dry weight	Sources
Phaeophyta		
Undaria pinnatifida	11–24	(Rupérez and Saura-Calixto 2001)
Laminaria digitata	8–16	(Marsham *et al*. 2007)
Laminaria saccharina	6–11	(Morrissey *et al.* 2001)
Fucus vesiculosus	5–10	(Rupérez and Saura-Calixto 2001)
Fucus serratus	17	(Marsham *et al*. 2007; Munda 1977)
A. nodosum	3–15	(Fleurence 1999; Morrissey *et al*. 2001)
Alaria esculenta	9–10	(Morrissey *et al*. 2001)
Himanthalia elongata	6–11	(Morrissey *et al*. 2001)
Rhodophyta		
Porphyra sp.	24–47	(Sánchez-Machado *et al.* 2004)
Chondrus crispus	11–20	(Rupérez and Saura-Calixto 2001)
Palmaria palmata	12–21	(Marsham 2007; Morgan *et al.* 1980)
Chlorophyta		
Ulva species	15–30	(Fleurence 2004)
Enteromorpha intestinalis	10–18	(Morrissey *et al.* 2001)

Source: Adapted from Good Food Institute India (2021)

Seaweeds can also provide the essential amino acids needed for human nutrition (Machado *et al.* 2020; Fleurence *et al*. 2018). EAAs of the red seaweed *Palmaria palmata* account for almost 46 percent of the total amino acid fraction, a proportion similar to that of egg white (ovalbumin) (Fleurence *et al*. 2018). In addition, many species already contain all nine EAAs – histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan and valine. The protein extracts of different species can be combined as blends to offer more nutritionally suitable (or bioavailable) proportions of essential amino acids (Reynolds *et al*. 2022).

Seaweed-inclusive, alternative-protein products can benefit from a number of texturizing and stabilization functions that seaweeds themselves provide. For example, seaweed hydrocolloids are great agents for stabilizing, gelling, and binding together food ingredients. This can help with creating a wider range of food products in terms of texture and shape.

Seaweeds also provide environmental benefits because they can be cultivated without the use of freshwater, land, or fertilizers. There are many examples of seaweed's potential environmental impact compared to conventional protein production. For example, seaweed grown in Norway has been shown to have a significantly lower environmental impact and global warming potential than soy grown in Brazil (Koesling *et al*. 2021). It is suggested that one acre of seaweed can yield as much protein as five acres of soybeans.

Processing

Raw seaweed has poor protein digestibility for humans because of its complex polysaccharide cell walls. Processing is therefore needed to ensure cell disruption. Currently, the focus is on developing or improving methods of protein extraction to improve its bioavailability.

Extraction methods include physical processes – techniques such as sonication, microwaves, pulsed electric fields and biomechanics, and chemical processes – such as using acids, alkalines, and enzymes. High temperatures and harsh chemicals are best avoided because they risk denaturing the desirable proteins and amino acids.

Examples include cell disruption using enzymes like cellulase and xylanase on *Palmaria palmata* (Joubert and Fleurence 2008); and the use of homogenization and osmotic stress to obtain proteins from *Porphyra acanthosphora*, *Sargassum vulgare* and *Ulva fasciata* (Barbarino and Lourenço 2005). Chemical extraction using sodium hydroxide and hydrochloric acid has been demonstrated on *A. nodosum* (Harnedy and FitzGerald 2013; Jordan and Vilter 1991; Kadam *et al*. 2017). Table 19 summarizes extraction techniques, species used, and the resulting yields.

TABLE 19: Summary of extraction techniques, yields and co-products

Seaweed species	Extraction method	Yield	Co-products	Reference
1. *Laminaria digitata*	Enzymatic hydrolysis and fermentation	2.4-fold enrichment in residual biomass	Ethanol	(Hou *et al*. 2015)
2. *Ulva fasciata*	Thermo-alkaline treatment	11% dry weight	Sap, lipids, ulvan and cellulose	(Gajaria *et al*. 2017)
3. *Ulva lactuca*	High shear homogenisation	39.0 ± 6.2% dry weight	Carbohydrates	(Postma *et al*. 2018)
4. *Porphyra umbilicalis*	Aqueous-alkaline extraction	2.4% dry weight	Carrageenan, pectin, cellulose	(Wahlström *et al*. 2017)
5. *Ulva ohnoi*	Microwave assisted extraction	0.9 (relative to original biomass)	Salts, ulvan	(Magnusson *et al*. 2019)
6. *Ulva ohnoi*	High-voltage pulsed electric field, followed by alkaline extraction	1.26 ± 0.29% (15% yield relative to original biomass)	Starch, salts	(Prabhu *et al*. 2019)
7. *Sargassum vulgare*	Alkaline treatment	2.53 ± 0.2% dry weight biomass	Sap, alginic acid, salts	(Baghel *et al*. 2020)
8. *Eucheuma denticulatum*	Enzyme-assisted extraction and alkaline extraction	59.4 ± 1.41* extraction efficiency	Carrageenan	(Naseri *et al.* 2020)
9. *Ulva* sp.	Supercritical water extraction	5.8% dry weight	Ethanol and hydrochar	(Polikovsky *et al.* 2020)

Source: Gajaria and Mantri (2022)

The wide range of extraction methods and consequent yields, as well as co-products formed, goes some way to explaining the complexity of creating useful protein fractions from seaweed.

An assessment of the most common forms of alternative protein extraction is highlighted below.

TABLE 20: **Common protein extraction methods and their attributes. T = temperature, P = pressure**

	High pressure homogenisation	Ultrasonication	Chemical disruption	Enzymatic disruption	Bead milling	Pulsed Electric Field
Scalability	High	Low	Medium	Low	High	Medium
Operating cost	High	Medium	Low	High	High	Medium
Efficiency	High	Low	Medium	Medium	High	Low
Energy requirement	High	Medium	Low	Low	High	Medium
Residue	Particulates	Particulates	Chemical residue	Enzymatic residue	Particulates	None
Harsh conditions	High T*	Local high T and P			High T*	
Selectivity	Low	Low	High	High	Low	High

*temperature can be lowered upon modification of traditional equipment with an inbuilt cooling system
Source: Good Food Institute India (2021)

It is clear from both the variation in extraction efficiency, and the lack of a clear leader in economic efficiencies, that research into an efficient, low-cost, scalable, protein fractionation process is still in development. However, there are startups in the space who have been going ahead with protein extraction methods that they claim produce a 65–80 percent protein concentrate from *Palmaria palmata* (Hermans 2021).

Using a high protein seaweed species and a biorefinery concept, stakeholders interviewed for this report indicated that it is possible to collect 2–6 percent protein from wet seaweed.

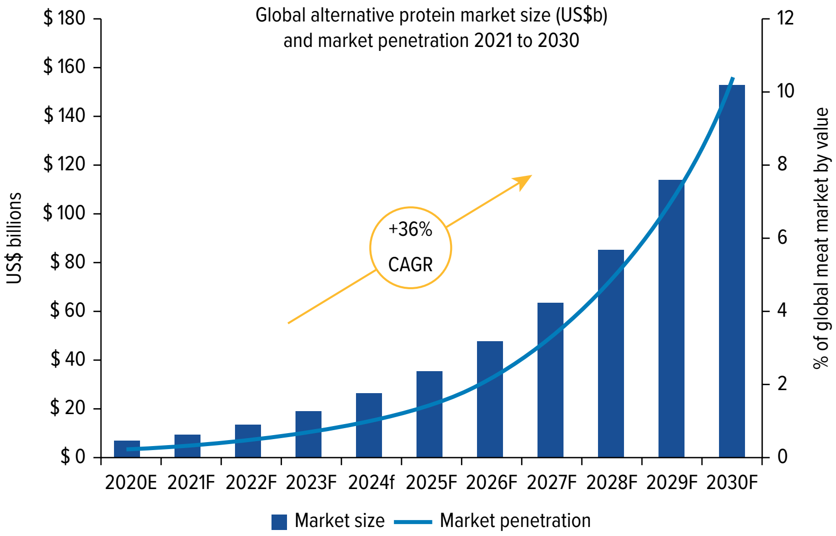
Market overview

According to EY's alternative protein report, the global alternative protein market was valued at 10.2 billion in 2022. As shown in the figure below, the market is expected to grow at a CAGR of 36 percent between now and 2030 (Dongoski 2021).

The two best-established protein sources on the market are both plant-based – soy and pea protein. The soy market is very well developed and receives significant investment. Pea protein is the second-largest market, with a CAGR of 30 percent from 2004 to 2019 (Bashi *et al*. 2019). Price points for these plant-based proteins are considerably cheaper than their alternatives, as shown in the Table 21 below.

In terms of financing, in 2021 alternative-protein companies secured $5 billion in disclosed investments. Some of the largest companies in this category include Impossible Foods and Beyond Meat. As shown in the figure below, the fermented, alternative-protein sector also received a large share of investment in 2021. The rising investment in fermentation and precision fermentation is expected to increase further over the next decade. Additionally, as prices of fermentation and cultivation technology fall, the fermented alternative proteins are expected to become very competitive with conventional proteins (Dongoski 2021). In the short term, however, cell-based meat products are not expected to achieve scale because the technology is still in its infancy.

FIGURE 17: Global alternative protein market size and market penetration to 2030



Source: Dongoski (2021)

TABLE 21: Prices [$/kg] of several alternative proteins

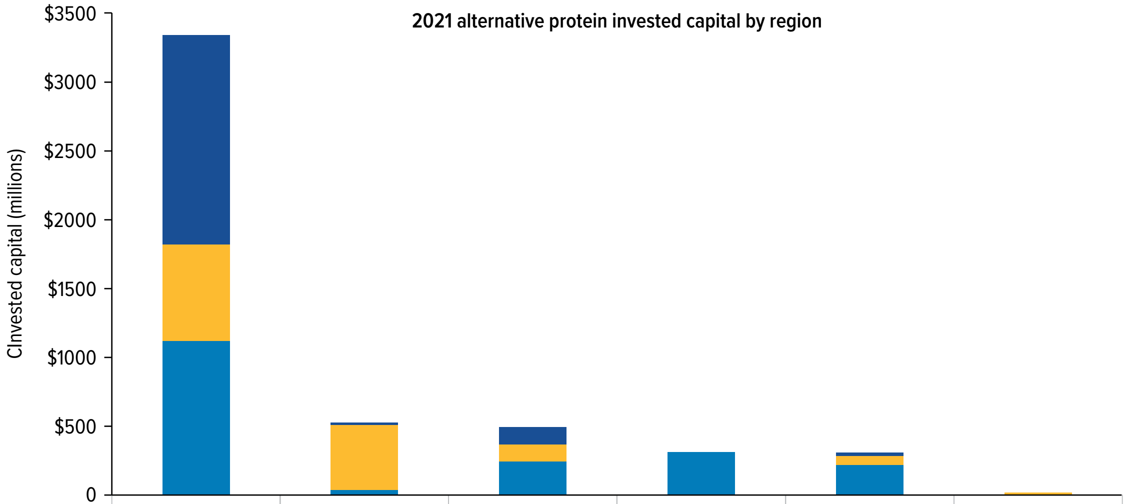
Type of protein	Price [$/kg] – 100% protein
Soy protein	2.0
Pea protein	5.0
Insect protein	41.0
Mycoprotein	13.0
Cultured meat	300.0
Whey protein	7.5

Source: Bashi *et al.* (2019)

There are a number of startups around the world developing alternative proteins from seaweed. For example, Brooklyn, New York-based AKUA (https://akua.co), originators of the world's first ocean-farmed kelp burger, and the Dutch Weed Burger, are both creating plant-based patties using seaweed. Meanwhile, Umaro is developing a high-protein bacon substitute derived from dulse (*Palmaria palmata*). Additionally, many developers are targeting seafood replacement products. From a marketing perspective, using ocean-sourced ingredients in seafood replacements is appealing. From a formulation perspective, there is less need to add ingredients to mask the taste and odor of seaweed.

There are typically two business models being used by startups to bring such products to market. First, there is a B2B sales channel model. This typically involves using a biorefinery process to isolate high protein content from seaweed, potentially with some functionality in the formulation. Developers in this category are either aiming to sell seaweed protein extract directly to other businesses, or are working on a royalty or licensing model with large formulation companies who in turn work with mass manufacturers of food products. This reduces the market risk and allows the developer to focus on the challenge of making an appealing, functional, protein replacement rather than on the final formulation, branding, distribution, and sales.

FIGURE 18: **2021 alternative protein invested capital by region. As shown in Buxton (2022), based on GFI report.**



	North America	Middle East	Europe	Latin America	Asia Pacific	Africa
🟦 Cultivated	$701	$475	$121	$0	$62	$17
🟨 Fermentation	$1,517	$16	$127		$30	
🟦 Plant-based	$1,121	$35	$248	$310	$220	
Total	$3.3B	$527M	$495M	$310M	$312M	$17M
YoY growth	+51%	+928%	–1%*	+177%	+92%	N/A

Second, there is a B2C model in which a company uses the inclusion of seaweed to market the sustainability of the product or to support health and nutritional claims. There are vertically integrated companies processing and developing seaweed-based alternative proteins, but the majority of startups in this category source seaweed directly from a network of farmers or processing companies.

Many of the entrepreneurs interviewed for this chapter are focusing on developing an alternative protein product alongside other potential applications – for example, polysaccharides. In these instances, the protein-based opportunity is almost seen as a lucrative valorization of waste stream opportunities.

Market dynamics

Drivers

1. Increasing awareness among product developers about the multi-functional benefits seaweed offers in alternative-protein food products.

Particularly when the ingredient contains hydrocolloids, there are stabilization, gelling and binding functions that seaweed can provide. These are valuable functionalities that are not offered by other protein sources, such as soy or pea protein. As one interviewee phrased it, “Why have a plant-based protein and sodium alginate on your ingredients list when they are both sourced from the same feedstock?”

2. Changing attitudes toward seaweed food products.

Although western consumers are less familiar with eating seaweed than Asians, there is a growing interest in this novel food category, and an improved understanding of the potential environmental advantages of seaweed products (Embling *et al.* 2022). Consumer acceptance of seaweed-based alternative protein products varies, depending on the level of inclusion, but in general the market outlook is positive. A UK-based study of consumers found that consumer perception of seaweed-based products (for example, bacon or burgers made from seaweed) was more positive than their perception of edible seaweed eaten without much processing (Embling *et al*. 2022).

3. Increasing interest in non-animal-derived food products, and more environmentally-friendly sources of alternative proteins.

Although plant-based proteins such as soy and pea protein are low cost and widely available, there is increasing pressure on supply chains and growing consumer awareness of their environmental drawbacks. There are concerns about the sustainable sourcing of soy protein, and it is also clear that protein yields from soy harvests are not consistent. Soil degradation and other environmental stress factors have recently led to some soy protein producers selling at about 35 percent protein content, down from about 45 percent in recent harvests.

Competition

Relatively speaking, using seaweed as a source of protein is still at an early stage of development compared to other alternatives. Seaweed typically does not have a very high protein content as a percentage of dry weight. However, as mentioned in the processing section, there are some species and startups that are showing promising extraction yields. Protein levels in various common sources of alternative protein are shown in the table below.

TABLE 22: Protein content of several alternative proteins

Type of protein		Protein content [%]	Reference
Plant-based	Soybean	~35–40	Qin *et al.* (2020)
	Pea	20–25	Lu et *al.* (2020)
Insect-based	*Telegryllus emma* (cricket)	~55	Gosh *et al*. (2017)
	Tenebrio molitor (larvae)	~53	Gosh *et al*. (2017)
Single-cell	*Saccaromyces cerevisiae* (sugarbeet bagasse)	45–49	Razzaq *et al*. (2020)

Source: Adapted from Siddiqui (2022)

Within the algae species, it is perhaps more common to find microalgae developers targeting the protein space, with *Spirulina* and *Chlorella* being used as nutritional supplements because they contain as much as 70 percent protein by dry weight. In the macroalgae world, the highest natural protein content, found in the genus *Porphyra*, falls well short of *Spirulina* and *Chlorella*: *Porphyra* can contain as much as 47 percent protein by dry weight (Rajauria *et al.* 2015). However, the competitive advantage of using macroalgae-based protein is that they tend to have a much higher micronutrient content, and the cost of production at scale may be far lower than microalgae, which require extensive on-land infrastructure and energy inputs to cultivate on an industrial scale.

However, seaweed's provisioning of all essential amino acids makes it a higher-value protein, competitive with whey and not just soy or pea. It may also provide a more competitive amino acid profile over microalgae, which may produce the complete set of nine amino acids but in smaller percentages.

In terms of price points for less processed products in the US, one stakeholder stated that 190g (or 6.7oz., a little under half a pound) of seaweed patties can sell for approximately $10 retail. This of course includes a mix of different ingredients, not just plain seaweed. For protein concentrates, another stakeholder stated that within the next few years, when it expects to be operating at scale, the company will be able to beat the price of more premium pork products (currently about $7/kg).

Challenges

There are multiple challenges for using seaweed in meat-replacement and seafood-replacement products.

1. Price remains a concern for several stakeholders. It is expensive to produce a protein concentrate from seaweed using current technology, and drying facilities need to be available close to farming sites. Seaweed proteins ultimately need to be price-competitive with soy-derived ones.
2. Seaweed has a lower protein concentration than alternative sources of biomass. There is a need to develop seaweed strains with higher protein content and improve cultivation methods for high-protein seaweed species.
3. Seaweed can have a large variability of protein content, depending on the season, temperature, and location. Trials with *P. palmata* harvested in France showed that protein levels varied from 9 to 25 percent, depending on the time of year (Bleakley and Hayes 2017).
4. Depending on the level of processing, heavy metal content in final products could be a concern. Mercury, arsenic, lead and cadmium could all pose health risks in seaweed-based products developed for human consumption (Bleakley and Hayes 2017).
5. Food neophobia – that is, fear of novel food items – reduces the willingness to try seaweed in parts of the world where it is not typically already part of the diet (Losada-Lopez *et al*. 2021).
6. The process of fractionating and extracting proteins from seaweed needs to improve to enhance protein production efficiency and to compete on cost and yield with other plant-based sources of protein.
7. The nutritional qualities of seaweed, beyond its protein content, must be demonstrated and must meet market needs.
8. Consumers must be willing to pay a "green premium," based on the comparative sustainability of seaweed production.
9. There needs to be greater demand from consumers. The formulation of more end products would help in this regard.

Regulations

The regulatory landscape for alternative proteins varies from country to country, and region to region. In several countries with a history of safe plant-based protein consumption, including China, plant-based proteins are not subject to pre-market approval requirements (GFI 2022).

In general, seaweeds fall under either a novel or non-novel food category. In Europe, a novel food can be a newly developed innovative food, or a food that is traditionally consumed but outside of the EU (ValgOrize 2019). Approximately 27 seaweed species are accepted as food in Europe, which may help with gaining regulatory approval for more processed seaweeds (Lähteenmäki-Uutela *et al.* 2021). Products that were not used for human consumption to a significant degree in the EU before 15 May, 1997 are classified as novel in accordance with Regulation (EU) No.

2015/2283. Although some reports state that the novel food status is not clear for any protein isolates or concentrates from approved macroalgae species (Lähteenmäki-Uutela *et al.* 2021), most foods derived from cell or tissue culture from animals, plants, microorganisms, fungi or algae, or produced by novel processes, are subject to novel food regulations.

Such foods require pre-market authorization and approval by the European Food Safety Authority (EFSA) before they can be marketed in any individual Member State (Leatherhead food research 2020).

Stakeholders in the US have previously maintained that startups extracting protein isolates and concentrates from seaweed may need to put together a Generally Recognized as Safe (GRAS) determination (Watson 2020). This means that the safety of the substance must be adequately shown through scientific procedures. The EU novel food regulation requires pre-market approval by governmental authorities; US GRAS does not. GRAS can be affirmed by an independent panel of recognized experts (Isbi 2019).

There are also strict rules globally governing heavy metal content in seaweed products. This should be monitored closely by companies exploring the production of alternative-protein products from seaweed.

Market outlook

The global alternative-protein market was valued at $10.2 billion in 2022 and is projected to see a 36 percent CAGR between 2022 and 2030. There are already examples of seaweed-based meat and seafood alternatives, and based on our analysis, the projected seaweed-based, alternative-protein market potential is $448 million by 2030. Nevertheless, there are some deal-breaker challenges that could stall growth in the market – namely, the cost of production of high-protein concentrates.

Although seaweeds are used in the formulation of alternative protein products, they are not always used as the main protein source. If a developer wants a product to have seaweed as its first named ingredient, it is typically in conjunction with soy- or pea-based protein.

Given the size of orders required by alternative-protein product manufacturers, some companies have suggested that they would need a facility capable of processing over 10,000 tons of wet seaweed per year in order to meet the needs of the bigger food manufacturers. They will also need to rely on high-protein seaweed species, and on potentially rotating the species on a seasonal basis.

According to many of the interviewees for this report, seaweed-based protein can reach cost and yield parity with pea protein, but this depends on the demand for seaweed-based ingredients growing and driving an increase in the cultivation of high-protein seaweeds such as *Porphyra* or *Palmaria palmata*.

When interviewees were asked how long it might take for seaweed-based alternative protein products to be commercially competitive and widely available, a five-year market horizon was repeatedly projected. One interviewee based in the US compared the current cost of dry kelp (around $1000/ton) with soy flour (around $300/ton), and argued that a three times cost reduction on the input side is feasible within five years assuming a processing system can meet the 10,000 ton per year capacity mentioned above. Product developers are working with their upstream providers, and most are aiming to ensure consistent quality and increased volumes of future seaweed supply.

4.7. Fabrics

Key highlights

Fabrics

Seaweed textiles (containing no more than 10 percent seaweed) that are based on Lyocell cellulose fiber (originally Tencel) are commercially available, but volumes remain too small for precise market sizing.

Global biosynthetic textile market: $17.18 billion in 2022.

Potential market growth: 10 percent CAGR between 2022 and 2030.

Potential seaweed-based synthetic textile market: $862 million in 2030.

Primary drivers

- Increased regulatory and market pressure for fashion industry companies to adopt more sustainable fabrics for their products.
- Corporate sustainability targets align with seaweed sustainability value proposition.

Main challenges

- Requires more sophisticated processing methods for higher seaweed inclusion rates, while improving performance.
- Competition from alternative sustainable materials with lower price points and better properties.
- Unavailability of sufficiently large seaweed volumes at a consistent level of quality and at low prices.

Potential deal-breaker challenges

- Cost of production.

Outlook: Although it is likely that the market share of Lyocell with seaweed extract will increase, for fabrics with a higher percentage of seaweed content to reach market, there will need to be performance improvements. One advantage is that seaweed-based fabrics can be easily blended with other bio-based feedstocks, such as cotton, to create fabrics that are competitive with conventional products.

Introduction

In the last few decades, “fast fashion” – standardized, mass-production fashion that is both rapidly produced and rapidly disposed of – has been a trend and driver of the fashion industry (Fletcher 2010; Todeschini *et al.* 2017). The business model of fast fashion has boosted the consumption of clothing, but it also comes with significant environmental costs (Todeschini *et al.* 2017). The fashion industry accounts for an estimated 2–8 percent of the world’s GHG emissions, consumes around 215 trillion liters of water per year, and accounts for approximately 9 percent of the losses of microplastics to the oceans (unfashionalliance.org).

Because of consumers’ growing interest in the environment, the concept of sustainable fashion – including the use of eco-friendly or recycled materials – is gaining importance in the fashion industry (Saricam *et al*. 2017). In this context, the fashion industry’s interest in using alternative materials such as seaweed for textile production has grown because of seaweed’s association with reducing GHG emissions, freshwater overuse, and water pollution.

BOX 6: FABRICS MARKET DEFINITIONS

Fiber: a filament that is many times longer than it is wide, used as the raw material to create yarn.

Yarn: a continuous length of interlocking fibers used to create textiles.

Textile: a woven texture created of interlocking strands of yarn.

Fabric: a type of textile, which has been finished and prepared for use in a garment.

Garment: an article of clothing composed of fabric.

Seaweed's value proposition

Using algae as a textile feedstock provides environmental services through the replacement of more environmentally harmful feedstocks, especially cotton and petroleum. Cotton's high water needs, for example, will prove an increasing challenge as the frequency, duration, and severity of droughts rise because of climate change. Petroleum-based textiles support the fossil fuel industry, despite recognition across the fashion sector that carbon emissions need to be addressed.

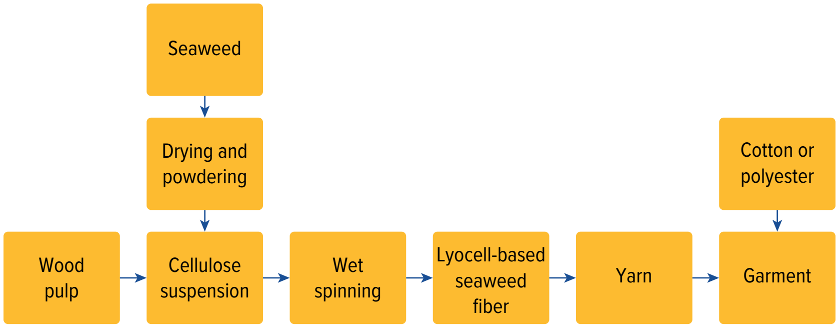
Although some people argue that seaweed-based textiles could be carbon-negative, others have expressed skepticism, with multiple interviewees noting that it is unclear to what extent carbon remains fixed in the product throughout its lifespan. For instance, while the enhanced biodegradability of seaweed-based textiles is a benefit for waste reduction, a biodegrading garment will ultimately release the carbon fixed in its fibers (Miller *et al*. 2007).

Processing

Seaweed-based textiles fall into one of two categories: a. cellulosic fibers with added seaweed extract, and b. fibers with algae as their main component. The former are available commercially, but they have only a small percentage of seaweed by mass – most of the product is comprised of Lyocell, a biodegradable fiber derived from wood pulp. On the other hand, the second type of seaweed-based textiles – fibers with seaweed as their main component – is currently being produced only at the pilot or research phase. In other words, garments made from alginate-based yarns are not yet commercially available. By contrast, garments made from Lyocell-based textiles with seaweed extract added are.

Lyocell-based seaweed textiles begin with wild-harvested brown seaweed (*A. nodosum*). SmartFiber, the primary producer of such textiles, sources its seaweed from Icelandic waters. It is then dried and processed with wood pulp into a fiber. Increasing the amount of seaweed in the product would make it less durable, especially in the presence of moisture (SmartFiber AG, n.d.). These fibers can then be spun into yarn and used in garments. SeaCell is combined with other fibers, primarily cotton, in varying amounts, which results in a variable percentage of seaweed in the final product. The highest proportion of seaweed included is about 10 percent, in clothes made from Vitadylan fiber, which is nearly identical to SeaCell (Gregersen *et al.* 2019).

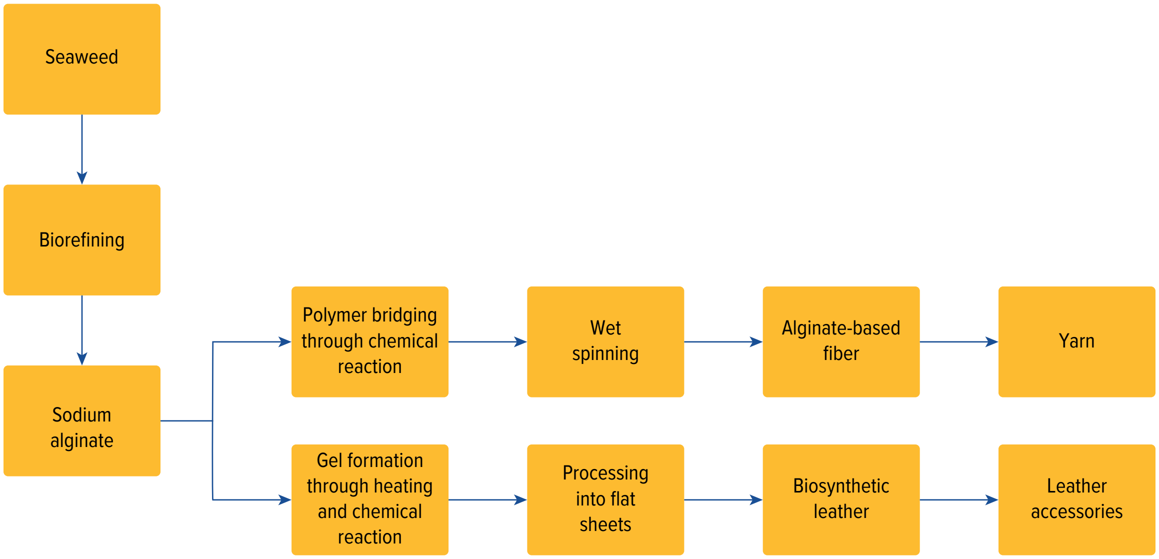
FIGURE 19: Process diagram for making Lyocell-based seaweed textiles



Source: Adapted from Gregersen *et al*. (2019)

The exact production processes for alginate-based, garment-ready textiles are currently proprietary because of the industry's early stage of development and hence its interest in protecting intellectual property. However, a general process description based on publicly available information can be found in Figure 20. Unlike Lyocell-based textiles, which are usable only as a replacement for woven textiles in the form of rayon-like knitwear made from yarn, alginate-based textiles can also produce bio-based leather.

FIGURE 20: Process diagram for making alginate-based yarns and leathers



Source: Figuly *et al.* (2022); University of Huddersfield (2021)
Note: Garments will likely be the primary end use for alginate-based yarns, but since such garments do not exist at the time of writing, yarn is listed as the final product instead.

Several interviewees at universities and startups stated that they were researching alternative methods for producing seaweed-based fibers, such as using proteins, polysaccharides, or monomers that are abundant in seaweed. At this stage, details are unavailable because of intellectual property concerns, and no papers or patents have been published. It is unclear when the first prototype textiles might be made with such technologies;

the interviewees only discussed these products in terms of early-stage scientific inquiry. Interviewees nonetheless noted that these products could use microalgae or non-kelp seaweeds as the feedstock because they have higher concentrations of the compounds needed to produce textiles. They projected that if the use of these alternative algae feedstocks can be commercialized, it would likely lead to more efficient use of raw materials and faster scaling of production.

To date, seaweed-based textiles have been used predominantly in garments, with limited applications in other categories such as household fabrics. Although some pilot projects have used the textiles in furniture or leather-based accessories, like wallets, these applications represent a small component of the seaweed-based textiles industry (University of Huddersfield 2021).

Market overview

In 2021, the global fiber market produced approximately 113 million tons, valued at nearly $1 trillion (Grand View Research 2022a). Synthetic fiber, the market segment that seaweed-based textiles aims to disrupt, represented 64 percent of the total market, or approximately 72 million tons, valued at more than $60 billion (Grand View Research 2022b). Polyester, the largest synthetic fiber, represents almost 85 percent of synthetic fiber production (Opperskalski and Riley 2022). Currently, the seaweed-based textile market is too small to be effectively sized.

TABLE 23: A comparison of different algae-based textiles

	Example products	Example companies	Algae percentage	Market readiness
Lyocell with seaweed extract	1) SeaCell 2) Vitadylan	1) SmartFiber AG 2) Grey Berlin	Up to 10%	Commercially available
Alginate-based textiles	3) Kelsun 4) Bio-based leather	3) Keel Labs 4) Uncommon Alchemy	High percentages, close to 100%	Prototyping, with limited commercial availability in 1–2 years
Textiles from other algae products	5) Microalgae-based yarn (Krebs 2020) 6) Monomer-based textiles	5) Algaeing 6) Piping Hot	Unknown, with possible percentages up to 100%	Research stage and early prototyping

Note: The products, and the companies that produce them, are numbered the same, based on data provided by the interviewees

There is increasing interest in producing textiles with seaweed-derived components but applications are currently at a pilot stage. Alginate, a compound abundant in brown seaweed, can be used to produce fibers. Alginate-based fibers are commercially available for wound dressings but as a gel rather than a traditional textile (Qin 2008). However, multiple efforts are under way to produce garment-ready textiles from alginate, most notably the work of Keel Labs, which has developed a yarn made predominantly from alginate. However, the product is still in the pilot phase and the company does not expect it to be commercially available until late 2023 or 2024.

Presently, the development of seaweed fabrics is being funded with early-stage investment from both the public and private sectors. Most interviewees from startups stated that they receive a combination of private and public funding. In recent years, government entities in the United States, the EU, and Australia have increasingly funded innovations in the seaweed industry through institutions such as the United States Department of Energy (USDOE), Innovate UK, and the Australian Research Council (Hermans 2022). Several prominent garment retailers, such as H&M and Adidas, have participated in Series A investments into companies developing seaweed-based textiles (Forrest 2022). Piping Hot, an Australian clothing retailer, has entered into a research agreement with scientists at the University of Technology Sydney to develop a fiber made from seaweed monomers. Piping Hot is looking to expand into the alternative fiber development sector, aiming to develop a scalable textile they can both use in their own products and sell to other interested clothing manufacturers.

The market for Lyocell-based seaweed textiles is too small for precise sizing. Interviewees expressed several reasons for this, but especially the lack of consumer awareness about the benefits of seaweed, and a limited supply chain for seaweed feedstocks. However, behavioral research suggests that heightened consumer awareness of the environmental impacts of a brand's products does not necessarily lead to new buying habits, especially if there is a high green premium price to be paid. As a result, it is unclear whether, and to what extent, greater awareness of seaweed's sustainability would increase market share (Warren 2021).

Interviewees also noted that the relatively low percentage of seaweed in Lyocell-based textiles could dampen interest in them, especially in the context of increased consumer scrutiny of product sustainability (Gregersen *et al.* 2019). A 2007 controversy, in which the *New York Times* claimed that there was no evidence of seaweed content in Lululemon's SeaCell product line, is a salient example and was mentioned in the interviews as a development that had a direct dampening effect on the growth of this market (Story 2007).

Besides Lululemon and Tommy Hilfiger – with their SeaCell product lines – Asics is the only other large clothing manufacturer collaborating with a producer of Lyocell-based seaweed fabrics. In 2022, Asics invested in Pyratex, a sustainable fashion company that includes SeaCell-based fabrics as part of their line (Style 2022). Two years earlier, in 2020, Asics released a limited run of yoga wear using Pyratex botanical dyes, but the partnership has yet to use SeaCell in any products (Pyratex 2022a). According to the Pyratex website, the company produces only five products made with their SeaCell fabric, which are retailed through small- and medium-sized fashion brands (Pyratex 2022b).

Early, limited-edition runs of garments will also be crucial to scale the algae-based textile market. Multiple interviewees noted that these limited-edition runs are important for getting consumers excited about seaweed-based products, even if they are often sold at a premium compared to other garments of similar quality. By producing a proof-of-concept run, startups can generate interest and promote greater investment across the supply chain. A template for such limited-edition runs is Adidas' Yeezy Foam RNNR, a shoe made partially from algae-based foam (Houser 2019) and launched in partnership with American musician Kanye West (https://www.livekindly.com/kanye-west-vegan-yeezy-shoes-algae). Partnerships with highly visible clothing retailers are especially important to raise a product's visibility.

Market dynamics

Drivers

Market interest in fabrics with higher seaweed inclusion rates is growing, driven by corporate sustainability targets, growing recognition of seaweed as a climate and environmental solution, and increasingly stringent sustainability reporting regulations. These regulations include the EU Corporate Sustainability Reporting Directive, which requires companies to report their impacts on and mitigation measures for climate change, local pollution, water and marine bodies, biodiversity and natural resources (Council of the EU 2022).

Spurred on by greater public scrutiny, their own internal sustainability goals, and new regulations that require proof of climate mitigation efforts or impose fines for “greenwashing” violations, large companies in the textiles value chain are seeking to make the textile industry more sustainable, especially fashion. (Greenwashing is the practice of making false, deceptive, unsubstantiated, or misleading statements about the environmental benefits of a product in order to create an impression about how environmentally friendly the product is.) Garment consumers are increasingly concerned about – and motivated by – sustainability, and analysts expect that in the coming years, 50 percent of the population will consider environmental impact as an important factor when choosing a garment (D’Arpizio *et al*. 2022).

Industry experts predict that fashion brands that remove barriers to – and accelerate the adoption of – sustainable textiles will be able to capitalize on these demand trends. They are further predicting that, in the coming years, the market will likely prioritize the growth of fully seaweed-based textiles, as opposed to Lyocell-based options, because of the comparative sustainability of the former. Fully seaweed-based fibers usually have greater environmental benefits than Lyocell-based textiles, and interviewees believe that increased scrutiny of company supply chains, stricter environmental standards, and internal sustainability programs will compel product managers to prioritize feedstocks with lower environmental footprints. However, in the event that other similarly environmentally-friendly alternatives arise with lower price points and better properties, it is not likely there will be substantial growth in seaweed-based textiles.

Competition

Over the next 5–10 years, other biosynthetic textiles will be the primary competitors to algae-based textiles. These products will have a similar price point and appeal to a similarly environmentally conscious market. In terms of their market readiness, they range from prototypes that are at the research stage to textiles with some commercial presence, albeit limited. Most of these alternative textiles that have sustained commercial markets in 2022 are made from agricultural crops, primarily corn; those with other bases do not yet have sustained market presence (that is, they are available at the development stage or in limited runs). Second-generation feedstocks represent a growing sector of bio-based synthetics. Other sources of bio-based synthetics, particularly fungi and agricultural waste products, are being investigated.

Although Lyocell-based seaweed fibers are available commercially, they have not been adopted broadly in the textile industry. The most common fiber of this type is SeaCell, developed by Nanonic (currently owned by SmartFiber), which is a blend of 85 percent Lyocell and 4 percent seaweed, with moisture accounting for the other 11 percent of the fiber’s mass. Lululemon and Tommy Hilfiger are the only large clothing retailers to include SeaCell in their product lines. Although the websites of both companies list SeaCell as part of their respective fabric options, it is not clear which of their products are currently being produced with SeaCell, if any.

Lyocell-based seaweed fabrics occupy a different market sector than textiles made predominantly from seaweed, so they do not compete in the same spaces. They are more likely to compete with other human-made cellulosic fibers and sustainable cotton options, which are cheaper and more widely available than bio-based synthetics (Textile Exchange 2022).

Generally, interviewees were unable to identify market-clearing prices or quantities in the interviews, nor were they able or willing to comment on financial aspects of their operations (for example production costs, costs of raw seaweed products, and so on).

TABLE 24: A comparison of available biosynthetic textiles

Feedstock	Raw material availability	Market readiness	Applications and performance	Environmental benefits	Example product
Food crops e.g. corn	Abundant, with an established supply chain for textiles	Sustained commercial availability	- Woven fabrics - Performance nearly identical to petroleum synthetics	- Disrupts petroleum textiles	Ingeo: fiber made from cornstarch, sugar cane, and beets (*Fiber to Fabric*)
Agricultural waste	Abundant, with variable supply chain for textiles depending on feedstock	Multiple limited runs	- Woven fabrics and leather - Requires waterproofing - Some durability concerns (Bananatex, n.d.)	- Disrupts petroleum textiles - Does not compete with food resources	Bananatex: fabric made from banana plant stalks and leaves
Fungi	Moderate, with limited supply chain for textiles (Bhavana and Roshan 2021; Deeg *et al.* 2017)	First limited runs presently available	- Leather - Requires waterproofing - Durability concerns (Deeg *et al*. 2017)	- Disrupts petroleum textiles - Does not compete with food resources - Indoor fungi production is unassociated with land use change	Mylo: leather made from mycelium (*Bolt Threads* 2022)
Algae	Highly dependent on species, with variable supply chain for textiles depending on species	Prototyping, limited runs by 2024	- Woven fabrics and leather - Requires waterproofing - Durability concerns for the leather	- Disrupts petroleum textiles - Unassociated with land use change - Does not require freshwater or fertilizer - Some species do not compete with food resources	Algiknit: made from kelp (Keel Labs 2022)

Source: Adapted from Opperskalski and Riley (2022) and from interview data, unless otherwise indicated

Challenges

1. Matching the performance of traditional textiles

Matching the performance of existing textiles presents an early hurdle for developing seaweed-based alternatives. For instance, alginate-based products are not inherently water-resistant. This presents a challenge when developing garment-ready textiles that need to withstand regular exposure to water. Interviewees working on novel seaweed-based products noted that, because of consumer expectations about product performance, it is difficult to develop textiles that perform as well as petroleum-based synthetics in terms of utility and durability. Another challenge is ensuring that seaweed-based textiles can seamlessly integrate into existing production lines. This is crucial to achieving scale and is a potential deal breaker if it cannot be achieved.

2. Availability and cost of raw material

More often than any other barrier, producers identified the availability of seaweed as a hurdle to scaling. Although production has not yet reached a high enough level for algal availability to become a limiting factor, several interviewees noted that substantial scaling might not be possible without an increase in the number of seaweed-growing operations and the establishment of a more robust supply chain for the raw materials needed to make seaweed-based textiles. Some predicted that seaweed availability would not prove a limiting factor for at least five years, while others predicted it would pose a hurdle sooner. Together with the current high cost of seaweed, this is a potential deal breaker for seaweed-based fabrics to ever compete with petroleum-based synthetics at scale.

3. Lack of public awareness

Market growth may also be limited by a lack of public awareness about seaweed's unique environmental benefits. Multiple interviewees expressed concern that consumers are unaware of algae's low environmental footprint compared to other biological textile feedstocks. As sustainability becomes an increasingly important motivation for garment consumers, more producers are marketing their clothes as sustainable, making it difficult for consumers to know which products are truly environmentally friendly. In the near- to mid-term, garments made from algae-based textiles will be sold at a premium owing to the market's limited economies of scale and the relatively high cost of feedstocks.

4. Lack of sustainability standards for bio-based textiles

Without standardizing bodies to verify claims of sustainability, producers of algae-based textiles have no way to prove the unique sustainability of their products compared to competitors who may be engaged in greenwashing claims. Interviewees noted that greenwashed products tend to be cheaper, and without a regulatory or voluntary standard to prove otherwise, the false promise of affordable, low-impact garments may draw consumers away from algae-based options.

5. Lack of traceability for seaweed raw material

Finally, interviewees noted that, because algae feedstocks are often difficult to trace, it is difficult to determine whether the algae are produced in a socially responsible manner. As social responsibility becomes an increasingly important factor for consumers, concerns about feedstock traceability could reduce interest.

Regulations

Most interviewees cited policy reform as one of the most effective methods for accelerating the growth of the algae-based textiles market. Reducing subsidies to environmentally harmful feedstocks, increasing those to novel sustainable sources, and enacting stricter requirements for the sustainability of textile supply chains were the most mentioned policy reforms. One interviewee noted that, following recently passed sustainability requirements for businesses in the EU, such as the Corporate Sustainability Reporting Directive, their business had seen a dramatic increase in the number of interested customers.

However, interviewees noted that without increased sustainability regulation and/or reductions in subsidies to petroleum-based synthetic feedstocks, reaching a competitive price and volume may well be impossible. Even with the introduction of such policy changes, interviewees suggest it would be at least a decade before algae-based textiles become cost-competitive with traditional synthetics.

Market outlook

The expected growth in algae-based textiles is part of a larger increase in biosynthetic textiles generally. Typically made from agricultural crops, and less frequently from forestry residue or agricultural waste, biosynthetic textiles are intended to disrupt fossil-based synthetics. Valued at $17.2 billion in 2022, biosynthetics currently account for less than 1 percent of the global textile market, but are expected to grow at an annual rate of 10 percent over the next five years (Opperskalski and Riley 2022).

The market's growth mirrors rising concerns about the climate impact of the fashion industry. As a feedstock that sequesters carbon, does not compete with food crops for arable land, and does not require freshwater, seaweed is better positioned from an environmental perspective than other bio-based feedstocks. However, it lags others in terms of value proposition and cost structure. To establish itself beyond a market with niche applications, it has substantial challenges to overcome. Whether this will happen is unclear, but if it does, it will likely be in the longer term because many other applications still need investment to scale beyond the laboratory stage. Even with the proper support network, interviewees do not expect seaweed-based textiles to be competitive with traditional synthetics within the next decade.

Corporations, especially fashion brands, are prioritizing investment in a diverse range of sustainable textiles in the hope of determining which options are best suited to their needs. Several large garment producers have indicated that algae-based textiles are one of many fabrics of interest. As an array of new bio-based products come online in the next two years, limited-edition runs will help determine which textile feedstocks are best suited to broad market adoption. Should seaweed-based products emerge as a particularly viable option, greater corporate investment in the value chain could help create a small, but sustained, commercial market.

Several startups plan to begin to launch pilot products and limited commercial runs over the next two years, with a focus on generating consumer and industry excitement. Over this timescale, developing partnerships with industry leaders will be vital for establishing a greater market presence and begin retailing limited-edition product lines. Building on this momentum, interviewees predict that a sustained commercial market for fully seaweed-based textiles will emerge in the late 2020s.

All interviewees agreed that to scale seaweed-based textiles to global market competitiveness, investment across the entire value chain is necessary. Although different interviewees identified different critical points for investing, seaweed aquaculture was the most frequently mentioned. Developing a more robust infrastructure for raw material supply will be crucial to ensure the cost reductions and supply levels necessary for broader commercial use in the next 5–10 years.

Funding for researchers investigating textile production with alternative, non-alginate seaweed compounds will be necessary to move these products from the research phase to the functional prototype phase. Meanwhile, funding for researchers investigating textile production with alternative algae bases, monomers, and non-alginate polysaccharides will be necessary to move these products from the research phase to the functional prototype phase. Interviewees indicated that without additional investments in research, it will not be possible to scale these novel seaweed-based textiles beyond the laboratory level. The early stage of research and current lack of commercial traction, explains why it is only a long-term potential market.

4.8. Bioplastics

Key highlights

Bioplastics

Seaweed-based bioplastic products have niche applications, mostly in form of biofilms, but volumes remain too small for precise market sizing.

Global bioplastic market: $11.5 billion

Projected market growth: 20 percent CAGR between 2022 and 2030.

Projected seaweed-based bioplastic market potential: $733 million in 2030.

Primary drivers

- Businesses are aiming globally to “go green” and achieve their carbon-neutrality goals.
- High R&D budgets and substantial venture capital (VC) investments.

Main challenges

- Integration into existing plastic supply chains is complex, unless technical performance can match incumbent products.
- Competition from alternative bio-based plastics with lower price points and better properties.
- Availability of sufficient seaweed volumes at consistent quality and low price.

Potential deal-breaker challenges

- Cost of production and process parameter requirements.

Outlook: There is evidence that innovators are working on compatible seaweed-based resins that could be integrated into existing production systems, but this process will take 5–10 years of R&D, and success is not guaranteed. In the short term, seaweed-based products may fulfil niche applications while they remain multiple times more expensive than competitive bioplastics.

Introduction

Plastics describe a wide range of semi-synthetic or synthetic substances that contain polymers derived from petrochemicals as their main ingredient. Modern society depends on plastics because of their many useful characteristics – they are light, flexible, durable, hygienic, and extremely versatile. Their ability to be molded and shaped has led to endless applications in packaging, transporting food and water, providing clothing and shelter, medical devices, vehicles, toys, and many daily consumer goods.

Bioplastics, or bio-based plastics, refer to materials that are based on a substance derived from living matter and present an alternative to conventional petroleum-based plastics. Bioplastics are made from polymers fully or partially developed from biomass. Potential raw materials for bioplastic production are plant-based materials, natural polymers (such as carbohydrates and proteins) and other small molecules such as disaccharides, other sugars, and fatty acids (Onen Cinar *et al*. 2020).

Today, 99 percent of the world's plastics are petroleum-based, with bioplastics representing only about 1 percent of the 390 million tons of plastic produced annually (Plastics Europe 2022). Presently, in most applications, petroleum-based plastics have technical properties superior to those of bio-based materials, and a lower cost of production. However, the widespread use of plastics has led to global pollution, as not all plastic material can be recycled, nor are enough waste management systems in place in many regions of the world. In particular, the rapidly increasing volumes of disposable plastic products have caught up with the world's ability to manage them responsibly. As a consequence, plastic pollution has become one of the world's most pressing environmental issues.

The need for more sustainable alternatives to conventional plastics is rising, and with more sophisticated materials, applications, and products emerging, the market for bio-based plastics is already growing (Plastics Europe 2022). Many of the bioplastic products on the market today come from first-generation feedstocks – which include edible crops such as sugarcane, sunflower, wheat and corn. The industry is also researching the use of non-food crops (second- and third-generation feedstocks) to produce bioplastics.

Seaweed's value proposition

As businesses look for alternative plastic materials, seaweeds have been considered as potential raw materials because of their rapid growth rates, large yields, and the lack of a need for cultivable land to grow them (Farghali *et al*. 2022). When seaweeds are grown for industrial uses, like bioplastics, many of their qualities – color, protein, other nutritional content – do not matter as much as they do in other use cases such as food.

Additionally, the abundance of biopolymers – in particular, hydrocolloids – in seaweed has contributed to an emerging interest in using them as raw material for the bioplastic packaging industry. These substances are characterized by their ability to form viscous dispersions and/or gels in water. Several of the common seaweed-sourced hydrocolloids are particularly useful as film-forming materials. Because of their superior mechanical and gas barrier properties, alginate and carrageenan biopolymers are frequently employed as biofilms – thin usually transparent sheets– and can be used to wrap or cover both food and non-food items.

Compared to conventional polymers used for food packaging, polysaccharide-based films have the advantage of being biodegradable, but they lack tensile strength and water resistance. Blending them with other biopolymers, however, can enhance the functionality of these polysaccharide-based films (Zhao *et al*. 2021). Not surprisingly, polysaccharide-based films are, in a sense, at the forefront of seaweed-based bioplastic development and are currently in technical and early-market adoption stages.

Numerous seaweed species have been used in bioplastic film production because of their high polysaccharide content. They include red seaweeds (*Eucheuma*, *Kappaphycus*, *Gracilaria*, *Porphyra*, *Pterocladia* and *Gelidium*), green seaweeds (*Enteromorpha*, *Ulva* and *Codium*) and brown seaweeds (*Laminaria*, *Lessonia*, *Macrocystis* and *Ascophyllum*) (Lomartire *et al.* 2022).

Processing

Different types of polysaccharides can be used in bioplastic production:

Alginate, extracted from brown seaweeds, is the compound most frequently used for bioplastic production. Alginates can be blended with starches to make biodegradable plastic films with low gas permeability and other desirable mechanical properties (Rosenboom *et al*. 2022).

*Aga*r-based edible films have been touted as potential alternatives to food packaging. However, the intrinsically poatissirmo-mechanical properties, such as thermal fragility and brittleness, have resulted in the use of reinforcements to improve their functional properties for such applications (Aswathi Mohan *et al.* 2022). Red algae, mostly *Gelidium* and *Gracilaria,* have previously been used in combination with other polymers and additives. However, there has been limited research in understanding the mechanical performance that agar alone can achieve. Experiments have been limited to a only small set of formulations using plasticizers, for example, agar and a plasticizer such as glycerol or sorbitol.

Carrageenan is a more common base material for bioplastics, especially for biofilms. Instead of using the whole seaweed, k-carrageen creates biofilms with better mechanical and physical properties. These are suitable for single-use packaging for powders, fast foods, candy, or pill casings that do not require advanced mechanical properties. Whole red seaweed-derived biofilms also have the technical capabilities to replace petroleum-based plastics (Lomartire *et al*. 2022).

Cellulose is also present in macroalgae but in much lower quantities than in terrestrial plants. For bioplastics, cellulose from seaweed has uniquely beneficial properties, including high tensile strength, stiffness, chemical resistance, water resistance, heat resistance, and inertness. Tensile strength and water resistance are desirable for packaging materials (Leong and Chang 2022) but the brittleness and difficulty in manufacturing cellulose-based plastics are a challenge.

The primary application for seaweed-based bioplastics currently being developed is for films and packaging. In addition to the use of polysaccharide-based films and the extraction of polymers directly from algal biomass, the fermentable sugars present in seaweed can also be used in the production of bio-based aliphatic polyesters, such as polylactic acid (PLA) and polyhydroxyalkanoates (PHAs).

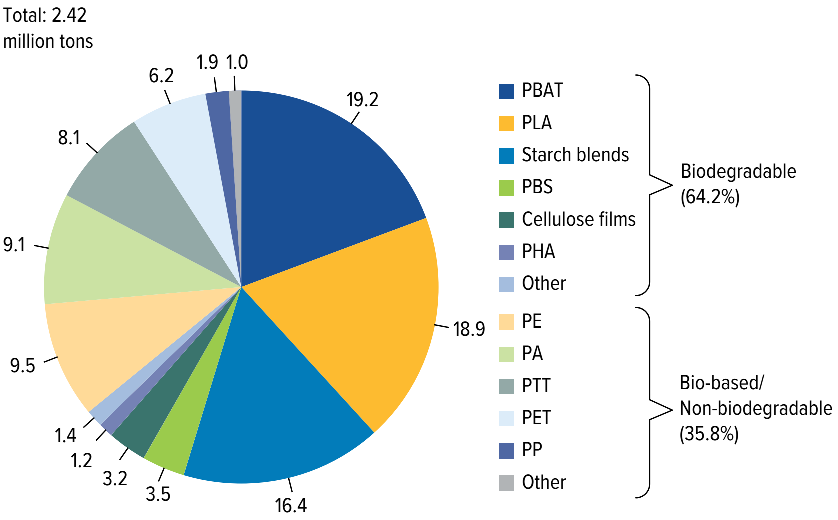
Furthermore, the development of seaweed-based plastic pellets is advancing. Plastic pellets are the most common raw material in the conventional plastic industry because they are easy to store and transport. These granules, 1–5 millimeters in diameter, are the building blocks of nearly every product made of plastic and can be processed and molded into a range of consumer goods. Replacing these with seaweed-based pellets would immensely expand market opportunities for seaweed bioplastics as they would be able to seamlessly integrate into existing plastic manufacturing machinery and processing lines. Approximately 10 tons of wet seaweed equates to one ton of seaweed-based pellets, according to one interviewee who produces PHBV polymers.

Although these niche seaweed bioplastic products could reduce plastic waste production, they will only be disruptive to the plastic industry as a whole if their production can be scaled up. Efforts toward biodegradability are beneficial for reducing the volume of packaging that ends up as pollution, but this should not be the only focus. Seaweed-based plastics should also aim to be long-lasting and simple in structure, so that when the product they are included in reaches the end of its life, they can be broken down and recycled into another product. The goal is to develop a seaweed-based bioplastic pellet that meets current standards and can be mold-injected to form various products using the same machinery that conventional plastics use today. However, such recycling-friendly properties might be in direct opposition to biodegradability goals.

Market overview

In 2021, global plastic production was 390.7 million tons, composed primarily of fossil-based plastics. Global bioplastic production in 2021 was around 2.41 million tons – equivalent to roughly 1 percent of the global plastics market (Plastics Europe 2022). By value, the global bioplastic market was estimated at $10.2 billion (GVR 2019).

FIGURE 21: Global production capacities of bioplastics by material type



Source: Plastics Europe (2022)

BOX 7: BIOPLASTICS MARKET DEFINITIONS

Starch, a polymer made of glucose, and starch blends account for the largest share of global bioplastic production capacities, representing 21 percent of total production in 2019 (Onen Cinar *et al*. 2020). Starch-based resins are used to produce films, injection moldings, and thermoplastic materials. Starch undergoes fermentation, producing ethanol and lactic acid, which is further processed and polymerized into PLA, PHA, and copolymers. Starch can be blended with synthetic degradable polymers and other biopolymers, such as PLA and PHA, to produce completely biodegradable polymer composite materials. However, at this time, these polymers are considered to be less resilient and offer lower water resistance than conventional plastics.

(Box Continued)

BOX 7: ***Continued***

PLA (polylactic acid) is a renewable, biocompatible, and bio-compostable polymer, meaning it needs specific conditions to initiate biodegradation. PLA is one of the most widely used polymers in bioplastics, and the current production capacity is more than 250,000 tons per year (Rosenboom *et al*. 2022). PLA is typically made through the polycondensation of lactic acid, which can be derived from the fermentation of sugars in sugar beets, whey, molasses, and seaweed (Hidawati *et al.* 2022). PLA can be produced to be optically transparent and has been used as a replacement for polyolefin (PO) films, as well as polystyrene (PS) foams, including incorporation into single-use items (Rosenboom *et al*. 2022).

PHAs (polyhydroxyalkanoates) are a family of bio-based and biodegradable polymers that are synthesized by microorganisms from various substrates as carbon sources, including using seaweeds and their associated bacteria. This group of polymers has diverse structures and properties, and over 150 types of PHAs can be synthesized by employing different bacterial species and growth conditions. The best-known polymers of the PHA family are **PHB** (polyhydroxybutyratepolyhydroxybutrate) and **PHBV** (polyhydroxyalkanoate). Compared to the PHB homopolymer, the PHBV copolymer has better physical properties such as impact-resistance, toughness, flexibility, and other properties that are beneficial in the manufacturing process. The diversity of PHAs' properties makes them suitable for a wide range of applications, including packaging, fibers, and biomedical uses (Reddy *et al.* 2013).

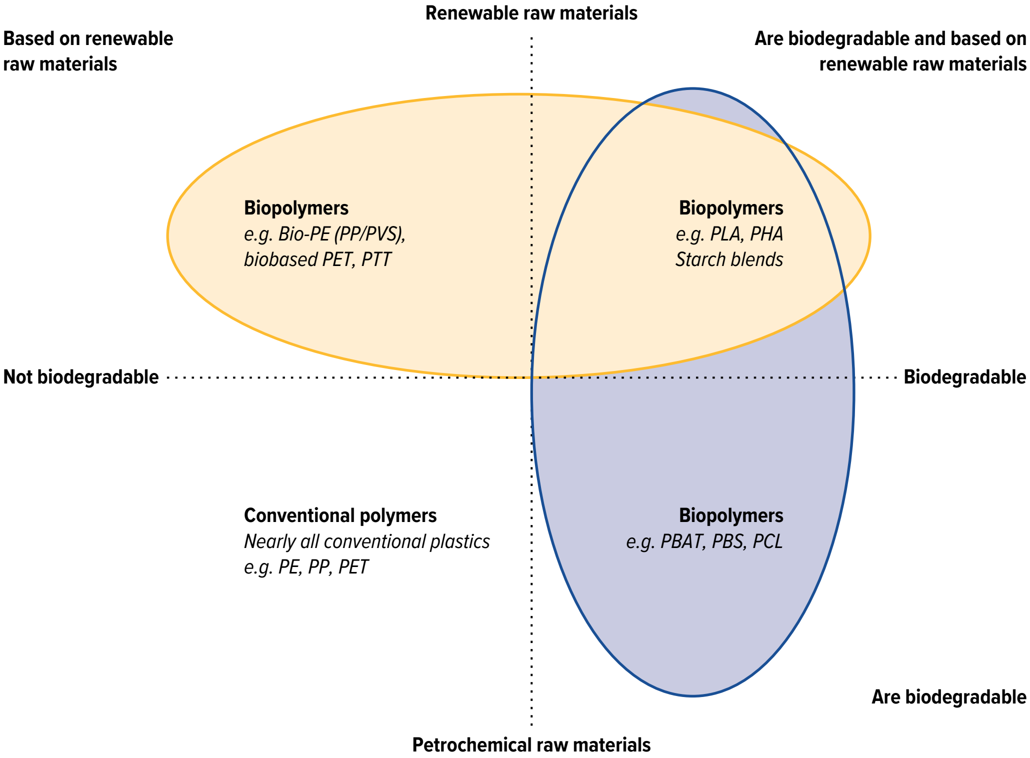
Bioplastic alternatives exist for almost every conventional plastic material and corresponding application and, like petroleum-based plastics, they are a diverse family of materials with different properties. As shown in Figure 22, there are three main groups of bioplastics:

- *Bio-based as well as biodegradable* – such as PLA and PHA or PBS
- *Only biodegradable* (petroleum-based yet biodegradable) – such as PBAT
- *Only bio-based* (non-biodegradable) – such as bio-based PE, PP, or PET (so-called drop-ins) and bio-based technical performance polymers, such as PTT or TPC-ET

Biodegradability refers to a material's ability to naturally degrade into basic components such as carbon dioxide, water, and biomass through the action of microorganisms (Moshood *et al.* 2022). This makes a biodegradable material's end-use more sustainable than alternatives. However, biodegradable properties are beneficial only if the waste management chains are able to handle this. Having biodegradable bioplastics among conventional ones might reduce the recycling rate, and some bioplastics require industrial composting.

Some examples of innovative, bio-based plastic polymers are PLA (polylactic acid), PHA (polyhydroxyalkanoates), PHB (polyhydroxybutrate), and plastics based on starch, cellulose, lignin, and chitosan (Nanda and Bharadvaja 2022). Starch and cellulose-blend bioplastics are widely available from corn and cassava, for example, while cellulose-based bioplastics are in the market as packaging films, eyeglass frames, food packaging, and other specialty materials (Nanda *et. al* 2021) The role of lignin and chitosan has been more of a reinforcement material in blends with biopolymers like cellulose and starch (Mariana *et. al* 2021).

FIGURE 22: **Types of bioplastics, both biodegradable and non-biodegradable**



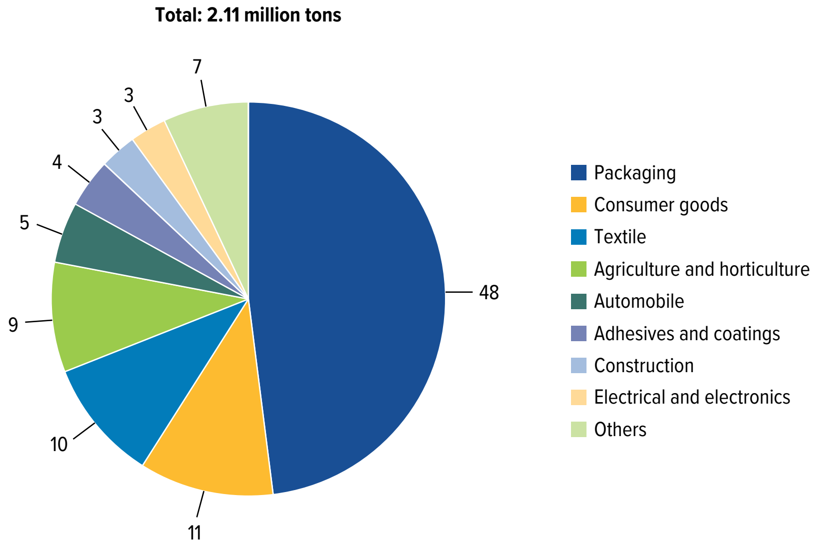
Source: Moshood *et al*. (2022)

Packaging dominates both the global plastic market for applications and the global bioplastic market (Ritchie 2018). In 2015, the industrial sector's leading global plastic waste was packaging, representing over 141 million tons – nearly half of all plastic waste. Additionally, most plastic packaging cannot be recycled; in 2015 only 14.6 percent of all plastic packaging was recycled, with the vast bulk of it either going into incinerators or landfills, or leaching into the ocean (Billerud, n.d.).

An estimated 95 percent of plastic packaging is single-use. From a sustainability perspective this creates the largest opportunity for bioplastic packaging to replace the conventional, fossil fuel-based packaging used today, with a bio-based, renewable product that is naturally degradable (Briley 2020). Food packaging and fast-moving consumer goods are the largest markets for short-lived and medium-lived plastics and bioplastics (Nanda and Bharadvaja 2022). Similar to the overall plastics market, packaging represented the largest market segment of bioplastics, with a share of 48 per cent (Plastics Europe 2022). Many notable multinational companies in various sectors have diversified their product portfolios and incorporated bioplastics in their packaging.

Benchmark prices for petroleum-based plastics range from $1/kg to $2/kg. By comparison, bioplastic currently range between $2–6/kg. The 20–100 percent higher cost of bioplastics is the major limiting factor in their growth. Most plastic components are derived from low-price commodities, often leading companies and consumers to decide to buy on price. The large price discrepancy between conventional and bioplastics reflects the fact that the production processes are not yet technologically advanced enough to reach economies of scale and reduce the polymerization cost for biopolymers (Nanda and Bharadvaja 2022). Petroleum-based plastics for use as packaging raw materials have a benchmark price of around $1.213/kg, according to the Mintec Global Packaging Index (2021).

FIGURE 23: Global production capacity of bioplastic in 2021, by market segment



Source: Plastics Europe (2022)

Market dynamics

Drivers

The market share of bioplastics is expected to increase as businesses aim to "go green" and achieve their carbon-neutrality goals. Despite the small share of the global plastics market, annual growth rates of 14–30 percent indicate that, in the future, bioplastics are likely to significantly influence the supply chain of plastics globally.

Primary application areas for bioplastics are the packaging industry, followed by the textile industry, automotive industry, and construction sector (Onen Cinar *et al*. 2020).

Incentivized by regulatory guidelines and consumer demand, consumer packaged goods (CPG) brands are stepping up initiatives to switch to sustainable packaging solutions (Ellsworth 2022). Collaborative organizations that are committed to adapting more recyclable or biodegradable types of packaging – including the New Plastics Economy, the Plant-Based Products Council, and the Bioplastics Feedstock Alliance – are attracting keen industry participation. Additionally, large consumer-focused corporations have developed and published sustainability targets that include reducing their plastic impact and incorporating alternative materials. These targets often include goals for 100 percent of their packaging to be recyclable, compostable, biodegradable, or reusable, and developing packaging alternatives using materials like seaweed fibers.

For instance, Walmart's sustainability goals include reaching "100 percent recyclable, reusable, or industrially compostable private-brand packaging by 2025" (Walmart 2022). Similarly, Nestlé's sustainability vision includes action on waste reduction, specifically, "95 percent of our packaging [is] to be designed for recycling by 2025 and [we] remain committed to achieving 100 percent. We are also reducing the use of newly made plastic – or virgin plastic – by one third by 2025" (Nestlé 2022).

Technology and innovation continue to improve the strength and other properties of bioplastics in areas where traditional plastics currently have an edge. Additionally, regulations like the EU's ban on single-use plastics (SUPs) and other restrictions will further support the adoption of bioplastics (European Commission 2022).

Distribution and target markets also vary within the seaweed bioplastics industry. The companies creating single-use premium niche products – like straws, sachets, takeaway boxes, and cups – often deal directly with consumers in a B2C approach. In contrast, those producing pellets and inputs for manufacturing to create higher-value products often work directly with plastic manufacturers in a B2B model.

Today, numerous companies exist that are developing niche seaweed-based bioplastic products and gaining attention for their novel, sustainable approaches. A number of interviewees mentioned that they are in the final stages of negotiations with conventional plastic manufacturers about the production of their seaweed-based polymer products.

Competition

Seaweed-derived bioplastic products will need to compete with established bioplastic manufacturers such as PTT MCC Biochem, NatureWorks LLC, Total Corbion PLA and Newlight Technologies, along with some small- and medium-sized global and regional players. Often using raw materials that are available at far lower prices and in higher volumes than seaweed, they produce primarily PLA, starch-based, and PHA bio-based materials. Although seaweed-based products will have to compete with these product categories on performance indicators such as level of biodegradability, heat resistance, strength, flexibility, and functionality as a barrier to air and water, price remains the most important factor for customers. This is particularly true in light of the fact that all bioplastics are perceived as more sustainable than conventional plastics and typically have green premiums.

The interviewees for the most part did not reveal any specific price points. However, one seaweed-based plastic startup did state that they can currently produce kelp-based plastics for around $5–6/kg, but to compete with other bioplastics and conventional plastics, the company is aiming to achieve $2-3/kg (Rydne 2020).

Conventional plastics find their way into nearly every consumer product. This presents a vast potential opportunity for seaweed to be incorporated into a variety of everyday products. Many of the startups in the seaweed bioplastic industry have a vision of replacing all plastics. For the time being, films or packaging, which are low value and high volume, appear to be their entry products. However, since seaweed bioplastics are still in the early stages of development, with limited available raw materials and a costly biorefinery process, they are essentially premium products in a low-price market. Nevertheless, interviewees predict that, in developing bioplastic products, biorefineries will be central to the business model.

Challenges

1. Cost and availability of raw material

Purchase price remains the driving factor for adopting new materials and methods by major packaging brands. Large companies now recognize seaweed as a novel plastic replacement material, and some have funds allocated to R&D in this space. However, they may still look to other established bioplastic feedstocks, which are less expensive. In turn, this sets price expectations for seaweed-based bioplastics, with adoption prices currently in the range of 20–40 percent higher than conventional plastics.

In addition to achieving a competitive price point, seaweed-based plastic companies must demonstrate the capacity to supply major packaging brands. To produce an entire product line, these brands typically request a commitment to provide hundreds, or thousands, of tons of seaweed-based pellets, which would require thousands, to tens of thousands, of tons of wet seaweed. This is a challenge, as it is currently not easy to source such volumes, especially outside the main seaweed-producing regions in Asia.

The importance of overcoming these challenges is that they are potential deal breakers, meaning that if they cannot be overcome, seaweed-based bioplastics will likely be unable to replace fossil-fuel based plastics at scale, but continue being a niche, premium product.

2. Matching the processing requirements and performance of conventional plastics

As seaweed-based plastics enter the market and companies consider employing these new materials, there are still challenges with chemistry and meeting the product performance criteria expected by consumers and manufacturers. The mechanical and barrier properties of seaweed packaging materials are presently not as good as those of today's conventional plastics. Properties to be considered include tensile strength, water vapor transmission rate, oxygen transmission rate, elongation at breakpoint, and melting temperature. Seaweed-based plastics will need to hold up to industry standards like the ASTM's plastic standards, which are instrumental in specifying, testing, and assessing the physical, mechanical and chemical properties of a wide variety of plastic products and their polymeric derivatives.

Ensuring that seaweed packaging can seamlessly integrate into existing production lines used for conventional packaging materials is also crucial for achieving scale and is another potential deal breaker if this cannot be achieved. Seaweed biopolymers will need to be processed and remain effective within the existing industrial methods, which include injection molding, [casting, and blow-film extrusion (Hanry and Surugau 2020). High-throughput processing plants have specific processing parameter requirements which need to be met.

In addition to industry standards, many individual food companies have their own internal and product-specific standards to ensure that any alternative packaging will keep the product inside it intact, undamaged, and unaltered. These include ensuring there is no transmission of ink from the packaging to the food within.

Moreover, desired functional characteristics such as being waterproof, water-resistant, stable, and sterile conflict with the other production goals in the development of seaweed bioplastics – in particular, improving and perfecting the property of post-disposal biodegradability. Synthetic chemicals may need to be added to achieve such properties, which in turn complicates recycling and processing and challenges the value proposition of seaweed bioplastics to be all-natural, not to mention being waterproof or water-resistance. In short, durability and stability conflict with biodegradability.

Regulations

Plastic production and performance are regulated by various required certifications as well as by the need to comply with global standards. Although these regulations do not specifically pertain to bioplastics, to be considered an approved and therefore widely accepted alternative, bioplastics ought to aim to meet these standards. Internationally accepted standards for plastics can be useful in guiding the development of seaweed-based bioplastics, and national policies can further serve to inform startups about minimum requirements for performance. Policies such as the European Union Directive on Single-Use Plastics, which bans certain single-use plastics for which alternatives are available, set a precedent for others to follow.

Major plastic standards and certifications include these:

- **ASTM International**: Formerly known as the American Society for Testing and Materials, these plastic standards are instrumental in specifying, testing, and assessing the physical, mechanical and chemical properties of a wide variety of materials and products that are made of plastic.
- **Biodegradable Products Institute (BPI)**: An independent certification program for products that meet all the requirements of the ASTM; applicable mainly in the US and Canada.
- **TÜV**: The European equivalent of the BPI, it provides an independent certification program for products that meet all the requirements of the EU.

Organizations committed to the advancement of alternative plastics include these:

- **Global Plastic Platform (GPAP)**: Harnesses the convening power of the World Economic Forum to bring together governments, businesses, and civil society to translate commitments into meaningful action.
- **The New Plastic Economy Global Commitment**: Led by the Ellen MacArthur Foundation, in collaboration with the UN Environment Program, the Global Commitment has united more than 500 organizations behind a shared vision of a circular economy for plastics.
- **The UK Plastics Pact**: The Pact brings together businesses from the entire plastics value chain, alongside the UK government and NGOs, to tackle the scourge of plastic waste.
- **Alliance to End Plastic Waste**: The Alliance is committed to ending plastic waste through collaboration and collective action.
- **Commonwealth Clean Ocean Alliance**: CCOA is committed to eradicating the growing threat of plastics to the marine ecosystem.
- **#breakfreefromplastic**: BFFP is a global movement envisioning a future free from plastic pollution.

In interviews with seaweed-based bioplastic developers, one core challenge was the complexity of the plastics industry and hence the difficulty of ensuring that they can produce plastic of commercial interest. From food packaging, to pellets, to consumer-ready goods such as cups and straws, there is bewildering variety of configurations and required functionalities in the target market for bioplastics, each with different factors and priorities that influence demand. Selecting and focusing on the desired market will be crucial for seaweed-based bioplastic producers, as will be learning the nuances and market influences that exist both locally and globally.

Market outlook

The growing awareness that plastic pollution is one of the major global challenges, coupled with the dependency of a wide range of industry sectors on plastics, means that there already is, and will continue to be, a strong demand for alternatives such as biodegradable plastics made from natural resources.

The total global bioplastics and biopolymers market is predicted to grow from $11.5 billion in 2022 to around $49 billion by 2030, at a CAGR of approximately 20 percent (based on an average of a set of different CAGRs ranging from 14 to 30 percent. The market model predicts a seaweed-based market share of $733 million by 2030. This is in line with another report (Ferrell 2022), which valued the seaweed-based packaging market at $180.78 million in 2021 and expects it to reach $613.42 million by 2029, with a growth rate of 16.5 percent during this period.

Seaweed-based bioplastics represent one niche within the bioplastics sphere where progress is being made. The number of startups has grown significantly over the past decade. Phyconomy notes that there are 44 startups creating applications for seaweed bioplastics. Investment trends have experienced a significant increase just between 2021 and 2022, with the number of new investments more than doubling and a 36 percent increase in the total disclosed amount invested (Phyconomy 2022). However, bioplastic innovation from seaweed is mostly performed by startups and not by large multinational corporations. The number and size of companies producing seaweed-based bioplastics will have to grow exponentially for bioplastics to become readily available and economically viable alternatives to existing plastics. On the other hand, until the larger corporations grasp the opportunity, there is a good chance that bioplastics might just remain a niche market segment for premium products.

Seaweed-based bioplastics can only have a measurable impact and become normalized and competitive in the global bioplastics market if all of the deal-breaker challenges mentioned and discussed above can be overcome, in particular, the cost of production, supply availability, specification of end products, and ensuring that process parameter requirements are met.

4.9. Pharmaceuticals

Key highlights

Pharmaceuticals

There are no commercial seaweed-based pharmaceuticals yet.

Global marine-derived pharmaceutical market: $2.56 billion in 2022.

Predicted market growth: 5–10 percent CAGR between 2022 and 2030.

Primary drivers

- Increasing demand for effective and innovative therapies.

Main challenges

- Long timelines to perform clinical trials and overcome regulatory hurdles.
- Capital requirements of R&D and clinical trials.
- Some competition from microalgae-derived compounds, for example, fucoxanthin.

Potential deal-breaker challenges

- Several of the larger seaweed-based bioactives currently under investigation suffer from batch-to-batch variability and the associated challenges of preparing high pharma-grade material.

Outlook: Since most of the work on seaweed-based pharmaceuticals is preclinical, it is expected that seaweed-based pharmaceuticals are at least 5–10 years away from becoming approved pharmaceuticals. It will require significant financing to progress.

Introduction

Historically, nature has been a rich provider of bioactive compounds for drug development. Today, modern medicine also includes cell-based therapies, regenerative medicine, artificial tissues, and genes often referred to as advanced therapy medicinal products (ATMPs) (Hanna *et al*. 2016), but it was not so long ago that all compounds used as pharmaceuticals were natural products. Indeed, over a period spanning many centuries, many bioactive and beneficial plant-based remedies have been discovered. It is these discoveries that form the foundation of modern medicine and, today, about a third of all small-molecule drugs in use are derived from natural sources (Newman and Cragg 2020).

The efficacy and contribution of natural compounds in treating various medical conditions differs widely, but in the area of infectious disease management, about 50 percent of all antibiotics in use are based on natural products (Newman and Cragg 2020). In some areas of medicine, this figure is even higher.In the field of oncology, for example, nearly two-thirds of all cancer treatment drugs are based on natural products. It highlights not only how much research and development has been devoted to finding anticancer remedies but, more fundamentally, the potency of nature's ability to offer the humans cytotoxic (cancer-killing) compounds (Newman and Cragg 2020).

Historically, all drugs had a terrestrial origin. It is only in the last 70 years that research has turned to the study of natural bioactive marine products (Gerwick and Moore 2012; Svenson 2013 By 2021, more than 30,000 natural marine products had been reported in the scientific literature. These discoveries have thus far generated 15 compounds that have been approved by the United States FDA as drugs for human use (Banerjee *et al.* 2022).

In addition, more than 300 patents related to marine drug development have been approved globally, and there are a large number of marine substances at different stages of clinical trial (Banerjee *et al*. 2022). Of the approved marine drugs, 60 percent target cancer, and a phylogenetic analysis of shortlisted patents for various therapeutic bioactivities suggests that 55 percent of the active compounds have been isolated from marine fungi, followed by marine bacteria and sponges (Banerjee *et al.* 2022). Often, the producer of the bioactive compound is a marine microorganism that has been isolated from a larger marine microorganism (Gerwick and Moore 2012).

Seaweed's value proposition

Seaweeds have been used as alternative medicines since ancient times. Currently, seaweed-derived bioactive compounds, which are associated with – among other things – antioxidant, antimicrobial and antiviral properties, have gained attention in medical research (Lomartire and Gonçalves 2022). Besides applications in the food industry, the stabilizing, thickening, and gelling properties of carrageenan, agar, and alginate are also used in the pharmaceutical industry (Lomartire and Gonçalves 2022), depending on the quality grade. Agar, for instance, has different applications in the pharmaceutical sector. Medium-grade agar is used as a gel substrate in culture media, whereas in the highly purified substrate form (agarose), agar finds applications in separation processes in the field of molecular biology (for example, electrophoresis and gel chromatography) (Cardozo *et al*. 2007). Carrageenan and alginate find applications in drug formulation, thereby acting as encapsulating, taste masking, and release control agents (Polat *et al*. 2021). Furthermore, research studies on carrageenan have reported antitumor activities (Yuan *et al*. 2006) and therapeutic properties against symptoms of the common cold (Eccles *et al.* 2010).

Besides hydrocolloids, seaweeds provide a wide range of bioactive compounds, such as other polysaccharides (for example, fucoidan and ulvan), phlorotannins, polyunsaturated fatty acids, and carotenoids, which have been recognized in several studies for their neuroprotective, antidiabetic, antioxidant, anti-inflammatory, and/or antimicrobial properties (Polat *et al.* 2021; Shrestha *et al*. 2021).

This report focuses on such bioactive compounds for new drug development, rather than the drug delivery functions that seaweed-derived hydrocolloids already carry out.

The algal contribution to the marine drug lead pipeline is 4 percent, with approved compounds such as iota-carrageenan (used in medical devices) and the cytotoxic component of Adcetris and other antibody-drug-conjugates (ADCs) being derived from seaweed and cyanobacteria (Banerjee *et al*. 2022). Algal compounds in clinical trials show the potential of algal biomass for the discovery and production of drug leads (Banerjee *et al*. 2022). These include compounds such as neosaxitoxin for pain management (Rodriguez-Navarro *et al*. 2007) and the different approved marine fatty acid esters, currently isolated from fish. Despite the success of these small microalgal toxins, macroalgae are nevertheless still underrepresented in the pharmaceutical pipeline, and there are currently no FDA-approved seaweed drugs on the market.

The vast majority of approved drugs are secondary metabolites, which are small organic molecules often produced in response to external stimuli, stress, or competition (Gerwick and Moore 2012; Newman and Cragg 2016). Although examples of approved primary metabolites – such as proteins, lipids and carbohydrates – exist, these structural components have not historically been as frequently employed in the medical space to generate pharmaceuticals, given their size and complexity. In terms of medical applications of seaweeds, most of the products under development focus on structural components of the seaweeds, such as different carbohydrates and polyphenols (Gullón *et al*. 2020). These larger polymeric compounds have been reported as having a range of beneficial properties both *in vitro* and *in vivo* (Rosa *et al*. 2019; Wang *et al*. 2020).

Processing

The initial discovery and development of new drug leads or bioactive compounds require diverse knowledge, access to advanced equipment for chemical analysis (separation, identification and isolation), and biological assays to evaluate the bioactivity of the new compounds isolated (Balunas and Kinghorn 2005).

The process starts with the collection of biological materials, which are then traditionally extracted using solvents to generate enriched extracts of diverse polarity and composition (Svenson 2013). The effect of these extracts is evaluated against the desired molecular target (enzymes, receptors, protein-interactions) or in cell-based assays (bacteria, viruses, mammalian cells) in a screening process to establish if the extracts contain any bioactive components.

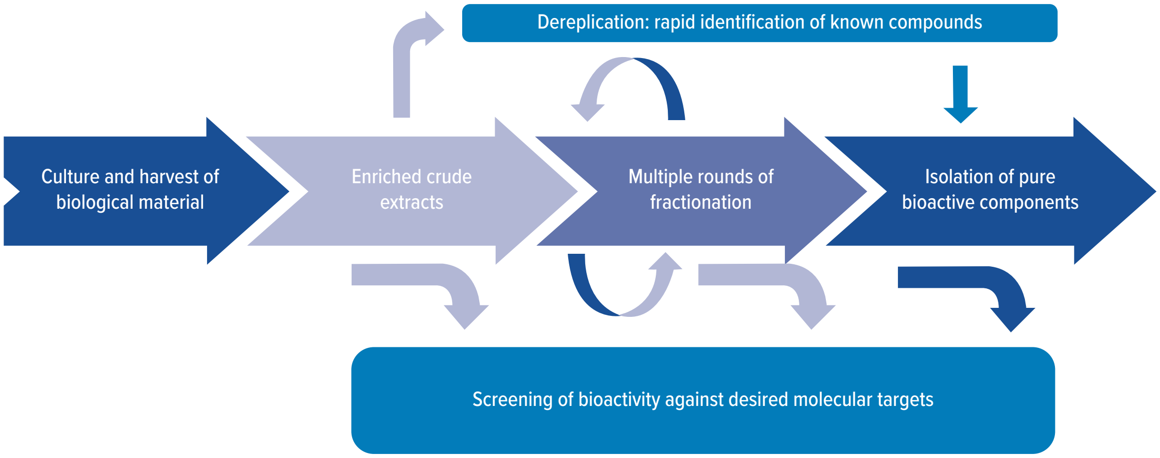
Subsequent extract fractionation (to reduce complexity) and retesting to verify the bioactivity allows for identification of the bioactive components. The identification early in the process, also known as dereplication, is key to determine whether the bioactive compounds are new or known ones. This process can be performed on mixtures for the isolation and identification of new chemical entities. However, isolation and identification are technically involving and are often not attempted until either an unknown novel structure or bioactivity has been documented (Svenson 2013). The isolated compounds are further evaluated in functional and toxicity studies *in vitro* and *in vivo* before they can be regarded as drug leads that can enter the established drug development pipeline.

Modern drug discovery also allows rapid screening of genetic material to identify known compounds or analogs thereof (Mahapatra *et al*. 2020). This represents a rapid tool for identifying biochemical pathways and known chemistries and compounds, but is less well suited to the discovery of entirely novel compounds (Niu and Li 2019).

Once a bioactive compound has been identified and is ready for clinical development, larger volumes of the compound are needed, but scaling up the production of some compounds can be challenging (Balunas and Kinghorn 2005; Devine *et al*. 2018). There are four methods employed to produce active pharmaceutical ingredients, depending on their origin and chemical structure.

Drugs are generally either synthesized or recombinantly produced (in microorganisms such as yeast or *E. coli*). A third option, direct biosynthesis from the producing organisms, is occasionally used to meet compound supply needs, even though most natural products are made in insufficient quantities for clinical use (Balunas and Kinghorn 2005). Semi-synthesis, where a precursor molecule is isolated and modified into the final product, is a fourth option (Ehrenworth and Peralta-Yahya 2017; Kennedy 2008).

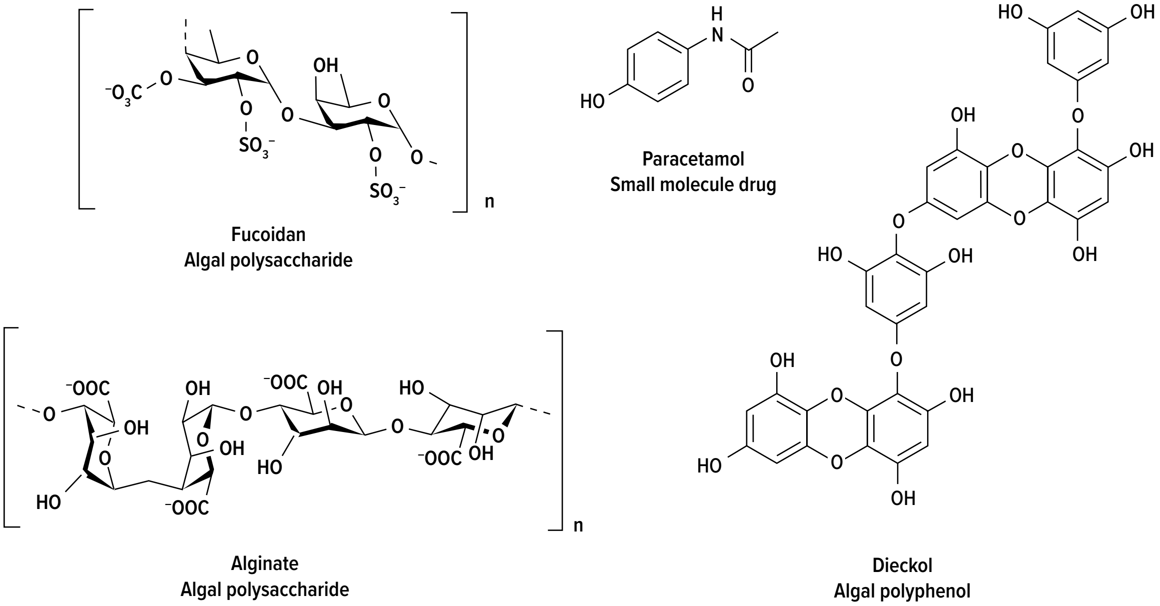
FIGURE 24: Process flow diagram for the development of pharmaceutical products



Source: Cawthron Institute (2022)

Direct biosynthesis and isolation from harvested or farmed biomass (depending on compound class) has often been used for seaweed compounds, in contrast to most other drug leads, which are produced synthetically after initial discovery (Rosa *et al*. 2019). This is mainly because of the polymeric chemical nature (large and complex compounds) of most seaweed bioactives under development (Rosa *et al*. 2019), as shown in Figure 25. Thus, from a production standpoint, it is expected that access to a steady supply of algal biomass will remain a key requirement for several types of algal components and compounds.

FIGURE 25: Chemical structures of seaweed-derived bioactive compounds



Fucoidan
Algal polysaccharide

Paracetamol
Small molecule drug

Alginate
Algal polysaccharide

Dieckol
Algal polyphenol

Note: This illustrates the differences in size between seaweed-derived bioactive compounds in clinical development (fucoidan, alginate and dieckol) and an approved small-molecule drug (paracetamol) prepared synthetically. The algal polymeric compounds can be 100 to 1,000 times larger than the classic small-molecule drugs.

Aside from having access to high-purity active pharmaceutical ingredients (APIs), a drug must be formulated in the correct proportions before it is ready for human use. The components of the final drug product will depend on the type of drug, the target, and the mode of administration – be it a pill, an injection, or a compound administered via an infusion pump (Elkordy *et al*. 2021).

Advanced therapy medicinal product (ATMP) technologies are providing additional alternatives to "traditional" drugs and seaweed components. Metabolites are also finding use in this area, as well as in the wider medical device space, which includes medical technologies and products frequently used on patients (Cunha and Grenha 2016; Hanna *et al*. 2016; Senni *et al*. 2011.

Market overview

The global medical market is massive, and the total global pharmaceutical market has been valued at over $1.4 trillion (González Peña *et al*. 2021). The global marine-derived drugs market was estimated at $2.57 billion in 2022 and is forecast to reach approximately $5 billion by 2030, with a CAGR of 8–10 percent (360researchreports 2022). Worldwide market revenues show strong historic growth, driven by the continued high demand for new pharmaceuticals and advanced therapies. As such, the pharmaceutical applications of seaweed-derived products represent a low-volume, high-value opportunity.

When these are combined with other medical applications, several high-value applications exist for promising seaweed-derived components. The majority of the revenue come from North America, especially the US pharmaceutical industry, which plays a leading role globally (González Peña *et al.* 2021). In terms of recent trends, however, the Chinese pharmaceutical industry is worldwide the fastest-growing. China and India are experiencing substantial population aging. This, along with today's more sedentary lifestyles, is putting more pressure on their national healthcare systems, which is driving the market's growth in these economies (González Peña *et al*. 2021).

Marine-derived drugs have only recently entered the market (Jiménez 2018), and there are currently no established seaweed-derived, government agency-approved drugs on the market. The situation is different in the medical device and drug delivery sector, and several companies are producing algal-derived polysaccharides for various applications. The sulfated polysaccharide iota-carrageenan, for example, is used as a high-molecular-weight viral entry barrier (Grassauer *et al*. 2008; Leibbrandt *et al*. 2010). Iota-carrageenan is produced in large volumes by several types of red seaweeds (Rhodophyta), such as *Kappaphycus* and *Eucheuma*, and has been developed for a range of medical applications by Austria-based Marinomed since 2006. In clinical trials, iota-carrageenan has been shown to reduce viral load in the nasal cavity, and it can be used prophylactically or for the symptomatic treatment of certain respiratory viruses (Grassauer *et al*. 2008; Leibbrandt *et al*. 2010).

The only seaweed-derived compound that has been approved as a drug – in China –is Oligomannate, a mixture of oligosaccharides, developed by the Chinese company Green Valley. Isolated from brown seaweed, it has been used since 2019 to treat the symptoms of mild-to-moderate Alzheimer's disease via a microbiome-modulating mechanism that works on the bacterial gut flora (Syed 2020; Wang *et al*. 2019). According to Green Valley: "GV-971 reduces peripheral and central inflammation by reconditioning the gut microbiota and inhibiting the abnormal balance of gut microbiota-derived metabolites." A large, phase-3, clinical trial by Green Valley in the US, the Green Memory study, was terminated in 2022 because of supply chain issues, and it is unclear when or if the clinical trials will continue. Other companies, such as Norway-based Algipharma and IFF (recently merged with Dupont Nutrition & Biosciences), are producing seaweed-based polysaccharides (alginates) as potential APIs for chronic obstructive pulmonary disease and cystic fibrosis, as well as for drug formulation and drug delivery (Cunha and Grenha 2016).

With the early stage of research in this area, most academic and commercial researchers and innovators are still working in the discovery and preclinical phases. The companies involved in commercial development are mostly small (fewer than 50 people). Large pharmaceutical companies are not yet as involved, although the Spanish company Pharmamar is specifically investigating marine compounds, including those isolated from algae (Haefner 2003; Hamann and Scheuer 1993).

The major focus is on seaweed polysaccharides, but exceptions, such as bioactive, smaller polyphenols, exist (Rosa *et al*. 2019). Many commercial companies (for example, Marinova, Glycomar, Biomara, PhycoHealth, and Olgram) are developing different types of sulfated polysaccharides for a range of medical applications (Laurienzo 2010; Senni *et al.* 2011). These sulfated polysaccharide compounds (for example, ulvan and fucoidan – see also chapter 4.5) can be isolated from a range of different seaweed species, such as *Ulva* and various brown seaweeds (Laurienzo 2010; Rosa *et al*. 2019).

large, negatively charged glycans are core components of seaweed cell walls but they can also be isolated from other marine sources in lower amounts (Senni *et al*. 2011). They have been used in human medicine for thousands of years.

Sulfated polysaccharides have been reported as having a range of bioactivities: they act atissuno-stimulants and antioxidants, and have a range of antibacterial, antiviral, anticancer and anti-inflammatory uses. They are often reported as among the prime opportunities for seaweed in the medical field (Wijesekara *et al*. 2011). Algal polysaccharides are also widely studied in the biomaterial sector for applications in wound-healing, regenerative medicine, and as biocompatible scaffolds for bioprinting and additive manufacturing (Bilal and Iqbal 2019).

Different bioactive effects of fucoidan have been reported in more than 2,000 peer-reviewed studies; it is a compound that attracts attention globally. The area of seaweed polysaccharides is well reviewed and detailed information about the different studied bioactivities is easily accessible (Laurienzo 2010; Rosa *et al*. 2019; Wijesekara *et al*. 2011).

Interesting activities are also seen in the area of polyphenols. These are a heterogeneous group of compounds (such as phenolic acids, tannins, flavonoids, stilbenes and lignans) that represent a major group of phytochemicals in the human diet. Polyphenols, like larger seaweed polysaccharides, have been linked to a wide range of bioactivities (Murray *et al.* 2018; Santos *et al*. 2019). Several seaweeds are rich producers of polyphenols; for example, several phlorotannins are being investigated for their ability to suppress cancer cell growth (Li *et al*. 2011; Santos *et al*. 2019).

Smaller compounds, such as halogenated furanones, have also been described as having a range of bioactivities and are still being studied (de Nys *et al*. 1993; Manefield *et al*. 2002). Furthermore, some macroalgae are also major producers of polyunsaturated fatty acids (Skrzypczyk *et al*. 2019).

Investigated compounds come from all divisions of seaweeds, but seemingly higher number of smaller compounds are reported from Rhodophyta (red seaweeds) than from Phaeophyceae (brown seaweeds) or Chlorophyta (green seaweeds) (Blunt *et al*. 2015).

Market dynamics

Drivers

Developing a novel “blockbuster drug” (that is, with annual sales exceeding $1 billion) is an attractive aspiration/ prospect for many.

An overview of price points of different seaweed-derived compounds based on purity is presented in Table 25.

TABLE 25: Market value of medically relevant seaweed-derived components of ranging purity
(SEE TABLE IN REFERENCES FOR SOURCES)

Class	Compound	Purity / Grade					Price range $/kg
		Unknown	Food	Research	Pharma	Analytical	
Small molecules and carotenoids[1]	Dieckol			x	x		62,000,000–975,000,000
	Lutein			x	x		> 97,500,000
						x	283,500,000
	Fucoxanthin			x	x		15,000,000
						x	53,500,000
	Fucoxanthinol					x	860,000,000
Poly- and oligosaccharides	Agar-agar	x	x				32.50–162
				x			215–540
					x		325–975
	Agarose	x	x	x			650–760
				x	x		1,840–4,330
						x	2,160–4,330
	Alginates	x					3.80–10.80
			x				49
				x			160–540
				x	x		37,875–1,000,100
	Carrageenans	x	x				10.80–49
				x			270–1625
	Fucoidans[2]	x					10.80–540
				x			346,275–432,700
				x	x		432,700–6,500,000
	Fucoidans[3]			x	x		6.400,000–13,000,000
	Ulvans			x			173,000–1,300,000
					x		1,22,250–4,165,500

[1] Usually sold in mg amounts [2] polysaccharides, no cut-off [3] oligosaccharides, cut-off < 10 kilo Dalton (kDa)

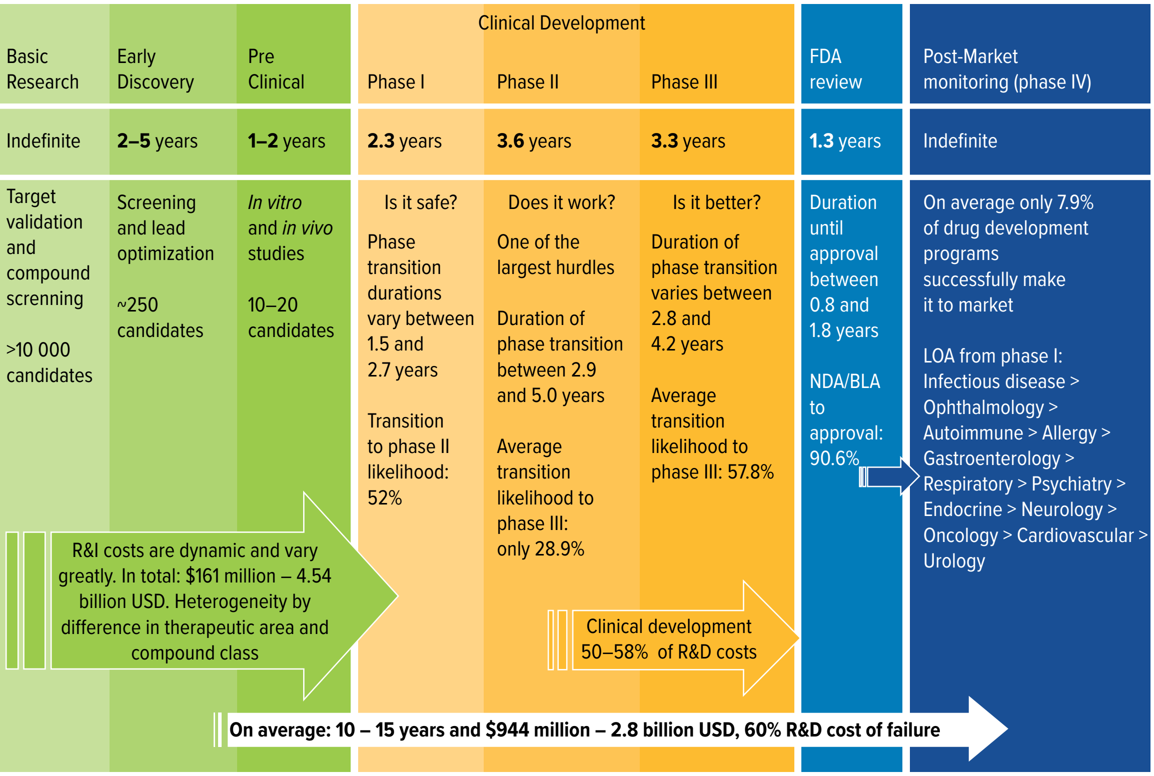
Competition

Because most seaweed bioactives and compounds in the medical sector are novel, they are being developed into brand-new applications and new therapies. This means that they are not necessarily replacing existing products in the same way that seaweed-based materials, fuels, or foods are. One exception may be in the area of lipids, where algal lipids could offer alternatives to lipids from fish (Skrzypczyk *et al*. 2019; Ward and Singh 2005). Several companies are pursuing the same type of compounds (fucoidan, ulvan, alginate, and carrageenan, for example) from different biomasses, which could create competition in this sector in the future.

Challenges

The potential benefits and profits are large when developing pharmaceuticals, but so are the risks. The actual cost of developing a new drug and bringing it to market is a controversial matter, with highly variable estimates that run the gamut. A comprehensible comparative study by Schandler *et al*. (2021) reported that, in 2019, the estimated R&D costs for bringing a novel chemical entity to the launch stage ranged from $161 million to $4.54 billion, with significant, therapeutic, area-specific estimates (for example, cancer drug development was especially expensive). Meanwhile, the average time to market ranges from 10 to 15 years (see Figure 26).

FIGURE 26: Drug development timeline and cost estimation diagram for pharmaceutical products



			Clinical Development				
Basic Research	Early Discovery	Pre Clinical	Phase I	Phase II	Phase III	FDA review	Post-Market monitoring (phase IV)
Indefinite	**2–5** years	**1–2** years	**2.3** years	**3.6** years	**3.3** years	**1.3** years	Indefinite
Target validation and compound screnning >10 000 candidates	Screening and lead optimization ~250 candidates	*In vitro* and *in vivo* studies 10–20 candidates	Is it safe? Phase transition durations vary between 1.5 and 2.7 years Transition to phase II likelihood: 52%	Does it work? One of the largest hurdles Duration of phase transition between 2.9 and 5.0 years Average transition likelihood to phase III: only 28.9%	Is it better? Duration of phase transition varies between 2.8 and 4.2 years Average transition likelihood to phase III: 57.8%	Duration until approval between 0.8 and 1.8 years NDA/BLA to approval: 90.6%	On average only 7.9% of drug development programs successfully make it to market LOA from phase I: Infectious disease > Ophthalmology > Autoimmune > Allergy > Gastroenterology > Respiratory > Psychiatry > Endocrine > Neurology > Oncology > Cardiovascular > Urology

R&I costs are dynamic and vary greatly. In total: $161 million – 4.54 billion USD. Heterogeneity by difference in therapeutic area and compound class

Clinical development 50–58% of R&D costs

On average: 10 – 15 years and $944 million – 2.8 billion USD, 60% R&D cost of failure

Source: Cawthron Institute (2022)
Note: The figure illustrates the stages and costs associated with bringing a bioactive compound onto the pharmaceutical market.

Clinical trials: The most significant entry barrier for any drug is successful passage through the three clinical trial stages. It is estimated that around 90 percent of drug leads fail their clinical trials (Harrison 2016). About half of the failures are ascribed to a lack of clinical efficacy, while toxicity and side effects account for a majority of the other failures (Harrison 2016).

Consistent, high-purity supply: For seaweed-derived bioactive compounds, supply and production issues present a substantial challenge (Hafting *et al*. 2015). Successful compounds that have been studied are often large, complex molecules, making it unlikely that they will be readily manufactured on a large scale through synthesis or recombinant technologies (Rosa *et al.* 2019). Some products therefore need to rely on wild or farmed seaweed, but these might not be available in sufficiently large quantities.

In addition, the polymeric nature of many of these compounds makes it highly challenging to obtain them in sufficient high purity (>98 percent for clinical applications). This is often reported as the major hurdle for advancing seaweed-based leads to *in vivo* and clinical studies. The sheer size of these polymeric compounds, as well as the wide range of reported molecular weights, make it difficult to obtain monodisperse polymers of high purity (Suprunchuk 2019). Contamination by smaller compounds of the same structure (smaller polymer fragments) is particularly troubling because they display the same chemical functionalities and are therefore hard to separate from the desired lead compound.

Although most farmed seaweed is currently grown in the ocean, some land-based farms exist that offer higher control over farming parameters. These may result in more control over product consistency and quality. Some of these land-based farms may also help to overcome to some degree the issue of seasonality, which triggers shifts in biomass composition as life stages and conditions change (Hafting *et al*. 2015; Suprunchuk 2019). This batch-to-batch variability is an obstacle for some medical applications. The greater control achieved by land-based production in reactors (used for microalgae) has been proposed as a solution for generating more predictable, more consistent, and more reliable starting material for pharmaceutical applications (Hafting *et al*. 2015). Seasonality can also cause supply issues for some applications, but this is less likely for small-volume pharmaceutical applications where an entire year's supply can be stockpiled after a single harvest.

Regulations: The pharmaceutical and medical sector is heavily regulated and seaweed-based compounds have to adhere to strict regulatory frameworks. The most obvious challenge cited during the interviews was the need for high-purity compounds for most medical applications. Entry into the pharmaceutical market will require a higher level of standardization, efficacy and traceability than has previously been required for most seaweed products (Hafting *et al.* 2015).

In some medical device applications, seaweed polysaccharides such as alginates and carrageenan can already be seen in commercial use. However, with the exception of oligomannate, the pharmaceutical pipeline is primarily at the discovery and preclinical stages. Thus, most the work in this area is at Technology Readiness Levels (TRLs) 1–4, spanning basic research to preclinical studies.

Market outlook

With no approved products currently on the market, making accurate projections in the algal pharmaceutical subsector is challenging, but just a single commercialized pharmaceutical product could generate significant revenue. Given the extremely high potential for error of trying to predict the development of seaweed-derived approved pharmaceuticals, this report did not perform a forecasting exercise for the pharmaceutical market. Generally, the global drug market's overall growth projection varies, depending on the type of drug, and an annual growth rate of 5–10 percent over the next five years (2022 to 2027) is frequently forecast. The increasing demand for effective and innovative therapies continues to drive long-term growth in the pharmaceutical area, especially for marine-derived drugs.

As most work on seaweed-based pharmaceuticals is preclinical, it is expected that these will be at least 5–10 years away from becoming approved pharmaceuticals. In any case, the route to market requires significant financing to progress and therefore heavily depends on the willingness of industry players to move seaweed-derived drug development forward.

4.10. Construction

Key highlights

Construction

Global green construction materials market: $312.5 billion in 2022.

Current seaweed market: There are examples of seaweed-based construction materials, but no data on market size are available.

Market growth: 10 percent CAGR between 2022–2030

Projected seaweed-based construction materials market potential: $1.4 billion in 2030.

Primary drivers

- Demand for green buildings which reduce use of finite resources.
- Potential for carbon sequestration in the built environment.
- Economic incentive from the tourism industry to deal with invasive algae blooms.

Main challenges

- Resistance to change from the industry.
- Inherent properties of seaweed, such as its tendency to absorb water in high humidity environments.

Potential deal-breaker challenges

- Cost of production and availability of supply.

Outlook: Seaweed construction materials show promise in niche applications such as fiberboard or bioplastic panels for interior design projects, for which premium prices can be charged. Recent changes to bio-based construction regulations have been favorable to this market sector, but this is considered a longer-term market because companies that operate in developing seaweed markets such as Europe often face limited biomass availability. In regions where seaweed is abundant such as the Caribbean with its *Sargassum* blooms, there has been significant interest in scaling up seaweed construction operations, driven by demand from buyers. For construction materials, it may be that products can also be generated through waste valorization in processing seaweed for other applications, and so its market forecast is uncertain.

Introduction

In 2021, the World Green Building Council estimated that the construction and operation of buildings accounted for approximately 40 percent of global carbon emissions, with 11 percent coming from materials and construction. (WorldGBC 2019). In response to this, startups around the world have been developing “green construction” materials with the goal of reducing construction’s harmful effects on the environment, minimizing carbon emissions associated with the construction process, and potentially sequestering CO_2 in the built environment.

Green building materials are environmentally-friendly substances that reduce the environmental impact of construction and improve the sustainability and efficiency of buildings. Popular green building materials include bamboo, hempcrete, straw bales, mycelium, wood, rammed earth, timbercrete, and grasscrete. To qualify as a green building material, it needs to be a locally sourced material that is natural, durable, reusable, or recyclable (Activesustainability n.d.).

These materials can be molded into a range of green construction products, including concrete and adobe bricks, which are among the oldest green building products on earth. They are made from tightly compacted blocks of sand, clay, and straw or grass, which then bake naturally under the sun without the need of an oven. The materials can also be used as bio-based fillers – potentially environmentally-friendly additives used in composites, compounds, polymers, paints, and adhesives. Environmental impacts associated with the production, distribution, use, and end-of-life phases of such green building products can be assessed through life cycle analyses. This chapter explores the use of macroalgae in green construction, architecture, and interior design.

Seaweed's value proposition

Marine biomass has been used in construction for centuries. For example, in the Middle Ages, women in Denmark created roof thatches made from eelgrass, also known as seagrass. The material is resistant to rot and can be used to insulate pitched roofs, interior walls, and building envelopes (Larsen 2019; Praveena and Muthadhi 2016). Unlike eelgrass, seaweed has not been widely used in construction, but whole seaweeds and seaweed extracts have properties which make them suitable as green construction materials,. They have been used as natural biopolymers, additives, viscosity-modifying admixtures (VMA), and filler materials to make a range of panels, bricks, concrete, and coatings (Praveena and Muthadhi 2016).

Seaweed extracts can improve the strength and durability of construction products. For example, alginate found in brown seaweeds has strong binding characteristics, which means it can be used as a potent adhesive for soil stabilization (Dove 2014; Galán-Marín *et al*. 2010). This helps it improve the physical properties of soils for geotechnical engineering, construction, and agricultural projects (Rossignolo *et al*. 2022). In 2010, researchers at the University of Seville, Spain, and the University of Strathclyde, Scotland, created bricks using sheep's wool, clay, and an alginate polymer derived from seaweed that are 37 percent stronger than traditional bricks (Galán-Marín, 2010). These wool-and-seaweed bricks, furthermore, did not require firing, resulting in energy savings during production.

Another study found that using algal ash as a filler in Portland cement mortars improved their mechanical performance (Azim 2016). Yet another found that using *Cladophora* sp. Nanofibers as reinforcement in Portland cement increased the bending strength of concrete (Cengiz *et al*. 2017). There are a handful of companies worldwide reinforcing construction materials with seaweed extracts, but most are at the research or pilot stage of development.

Polysaccharides can also be used to make bioplastics. For example, an alginate biopolymer can be combined with a plasticizer (for instance, glycerine), additives (for example, kelp, sand) and a solvent (water, for instance) to make bioplastic products for construction and interior design. Both milled, whole seaweed and seaweed extracts can be used to create bioplastics. The biomass is highly versatile. Thermoplastic, seaweed-based biopolymers are particularly desirable because they are highly malleable and can be used in a variety of product types. A number of startups, including WeedWare in the Netherlands, have explored the use of these as structural and interior design components such as flooring, paneling, and shade structures.

Several studies have highlighted the fire-resistant characteristics of seaweed. Polysaccharides found in seaweeds such as carrageenan can be made into fibers that act as excellent flame retardants. Because of this, a few startups have incorporated seaweed biopolymers into panels, bricks, and plasterboard products, with the aim of creating non-toxic, human-safe, and environmentally-friendly fire retardants to replace conventional, hazardous retardants (James Dyson Award 2021; Thomas 2023; Veneza 2021).

Whole seaweeds have been explored globally as additives in construction. For example, the company BlueGreen Mexico makes adobe building blocks – called Sargablocks – out of 40 percent *Sargassum* and 60 percent organic materials such asa adobe and clay. In compliance with federal regulations, Sargablocks can be used in standard construction and have been tested for durability and resistance. Studies conducted by the Quintana Roo State Secretariat of Ecology and Environment have shown that these bricks have a resistance of 75–120 kilogram-force per square centimeter and a durability of up to 120 years (Desrochers 2020; López Miranda *et al*. 2021). They have also been shown to withstand earthquakes and storms (*Material District* 2019) Similarly, the product SargaCreto is made with *Sargassum* blended with concrete. This is produced by Grupo Dakatso in Mexico (López Miranda *et al.* 2021; SargaCreto 2022). Sargacreto is made by dehydrating *Sargassum* and mixing itin a 40:60 ratio with concrete. It can be used to build vaults, joists, block, and sidewalks (López Miranda *et al*. 2021).

Various experiments have also demonstrated the role seaweed can play as an insulating material in construction and it is reported that Sargablocks provides good acoustic and insulation properties (Berglund *et al*. 2021). However, our interviewees highlighted issues with rotting in high humidity environments, which would limit the scope of seaweed's use in this way.

Seaweed can also be used to make panels. For example, in 2017, Alamsjah *et al.* used fibers from *Kappaphycus alvarezii* as an alternative to wood in the production of medium-density fiberboard (MDF). They described how this could contribute to forest preservation in Indonesia by reducing the demand for timber (Alamsjah *et al*. 2017; Rossignolo *et al*. 2022). Dutch startup BlueBlocks began collaborating with universities in 2017 to develop a sustainable, natural process for producing seaweed-based materials, including "SeaWood" panel products, a natural, compostable, and chemical-free fiberboard material that behaves like traditional wood. The company primarily uses brown seaweed because it is abundant in colder waters and can be sourced from various locations close to operations, which facilitates the scaling up of the project. To create the panels, dried seaweed is combined with a seaweed extract that acts as a natural binder, and with residual flows from the wood and paper processing industry. The plates are dried, pressed, and cured to create panels (The Exploded View.com). The company sells SeaWood as nonload bearing panels to small-scale projects and is currently formulating its pricing strategy.

An important aspect of using seaweed in construction is the potential to sequester carbon dioxide in the built environment. Buildings can last for centuries, so they offer a potentially promising pathway for carbon sequestration. Interior design elements like SeaWood have been touted as a route to such temporary storage of carbon. Similarly, as the second-most used substance or material on earth (after water), concrete represents a significant physical market and storage vessel for carbon. Carbon storage provided by bio-based materials could also extend beyond the usable lifetime of the building, if it is paired with material recycling and reuse.

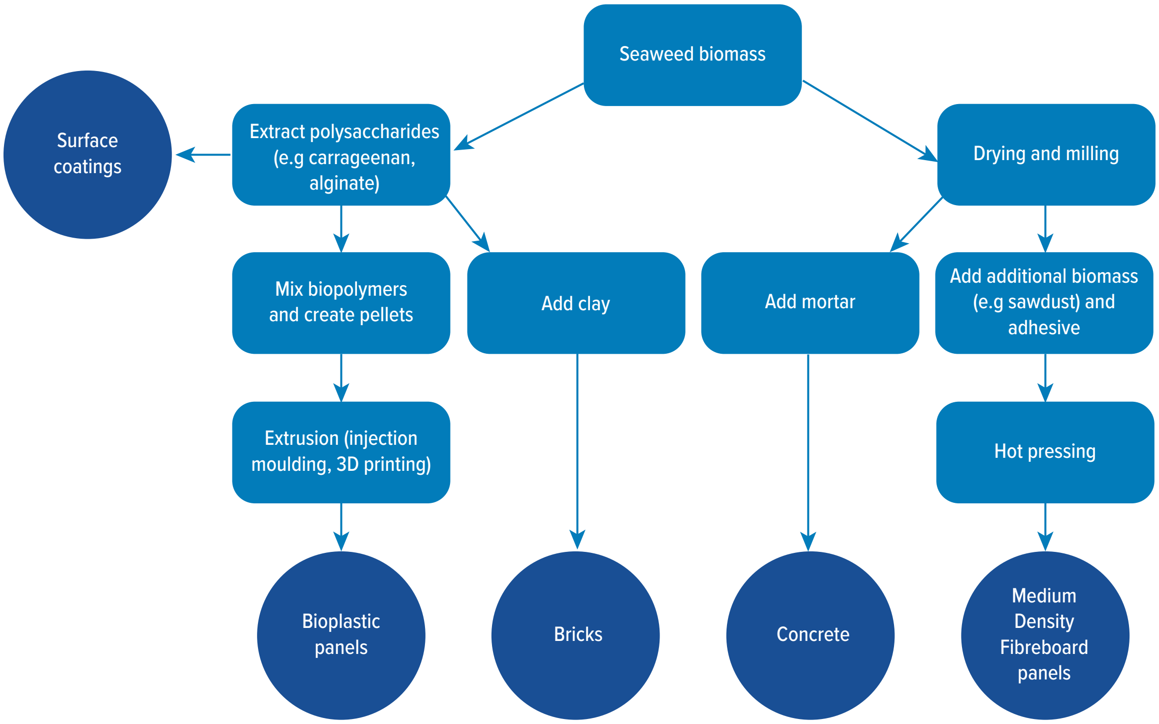
Processing

Seaweed for construction materials can come from wild-harvested or farmed sources. Waste macroalgae deemed unusable for consumption has also been used by startups working in this area.

Based on our research, companies exploring the construction applications of seaweed are distributed evenly around the world. However, in Europe, North America, East Asia and Oceania, there is a clearer focus on applying technology to extract useful components of seaweed such as alginate or carrageenan for construction. Low-tech processing pathways, such as drying and milling, are being implemented in all geographies.

In Europe and North America, several biorefineries have been employed to extract and separate macroalgae fibers and polysaccharides such as alginate, which can then be incorporated into various products, including bricks and bioplastics. Conversely, a handful of companies have been using minimally processed seaweed, such as Sargablocks or SargaCreto in Mexico (see Figure 27).

FIGURE 27: Examples of processing flows for seaweed-based construction materials



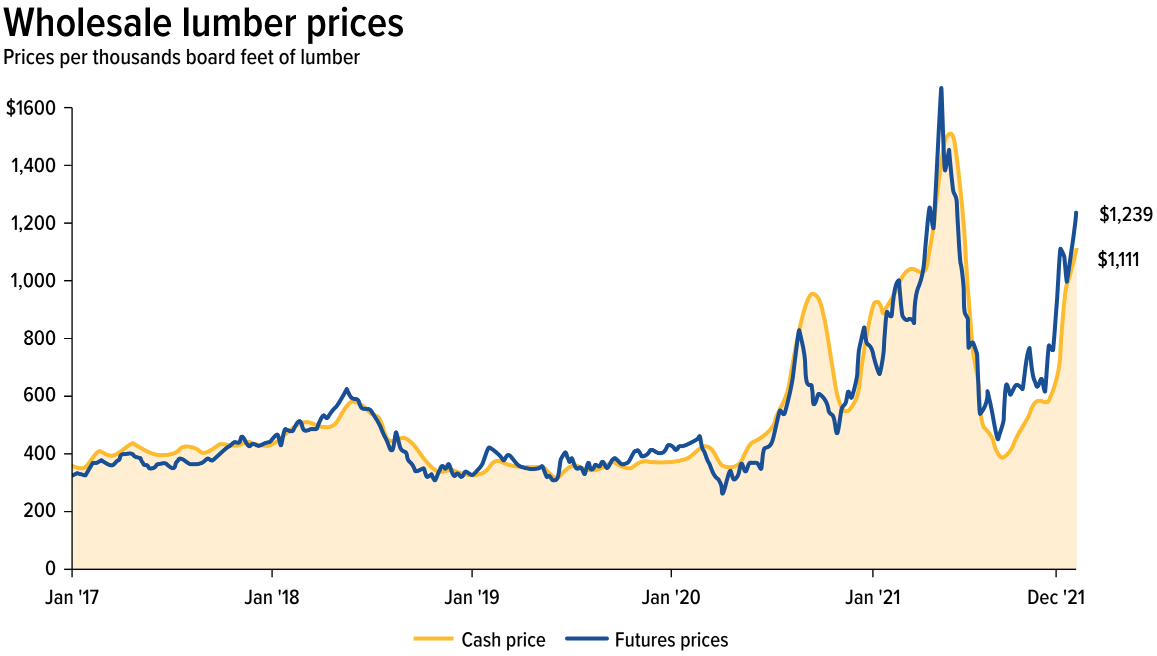
As mentioned above, the amount of seaweed included in an end product depends on the level of processing. Using whole seaweed, adobe blocks can contain up to 40 percent intact *Sargassum*, which is later dried in the sun. Meanwhile,, Wouthuyzen *et al.* (2016) stated that 2,133.5 tons wet weight of brown seaweed could yield 29.9 tons of alginate (a 14 percent conversion ratio) (Wouthuyzen *et al.* 2016). From there, some interviewees suggested that alginate could be included in bricks at up to 20 percent total weight. To account for this variation in the literature with regards to wet biomass to dry product conversion ratios, we take a middle-of-the-road perspective and estimate that 1 ton of wet seaweed could create 200 kilograms of seaweed-based construction product.

Market overview

In 2022, the global green building materials market was valued at $312.5 billion (IMARC n.d.). Reports indicate that the overall market remains relatively fragmented, with many small players owning small shares of the market. North America is considered the dominant market, but Asia-Pacific is showing high growth rates (IMARC n.d).

The price points of different bio-based and green construction materials vary. In addition, price points for many novel materials are not widely available. However, according to most stakeholders, wood remains the largest segment in this category. For comparison, Figure 28 shows the wholesale price points of lumber in the US. COVID-19 had a significant impact on the price volatility of many building materials. The price of lumber has since dropped back down to almost pre-COVID prices.

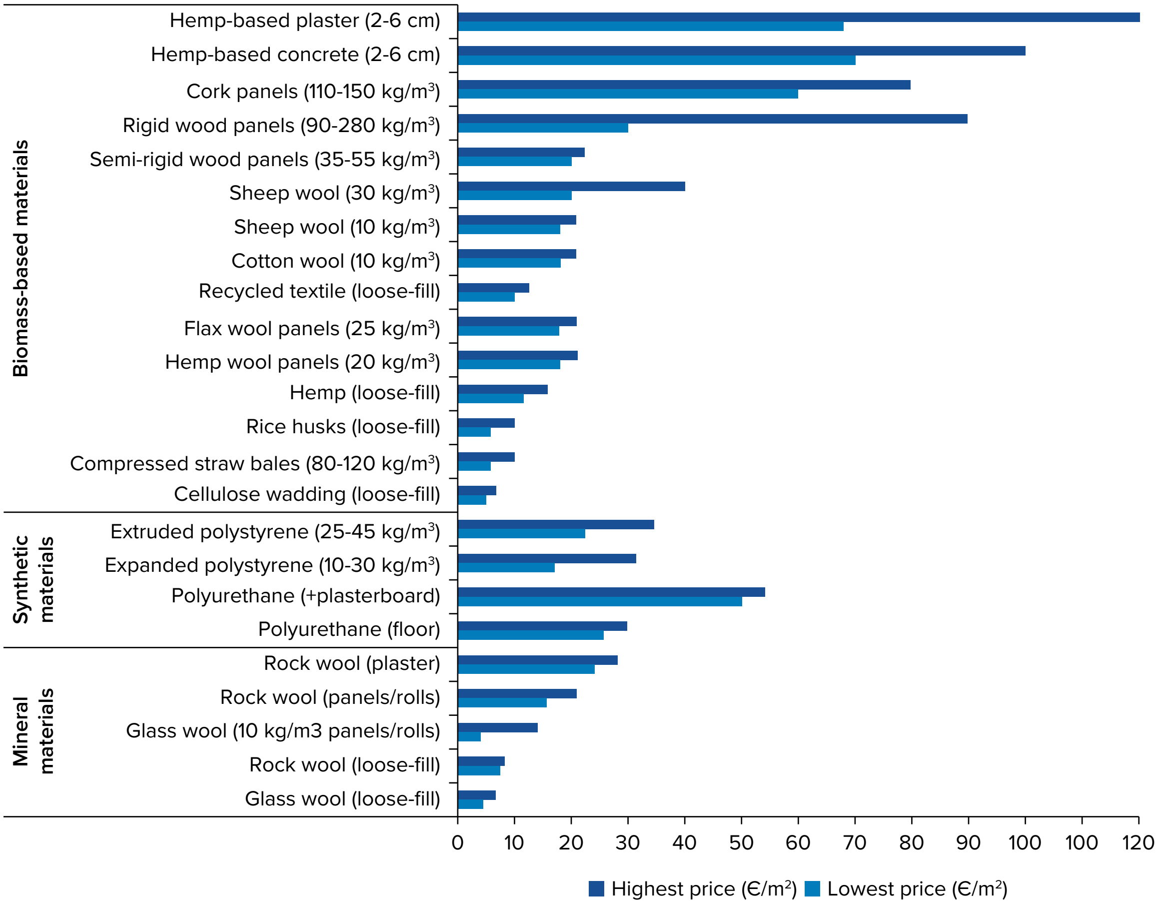
FIGURE 28: Comparison of wholesale lumber prices in the US, 2017–2021



Source: Lambert (2022)

In addition, Rabbat *et al.* have compared the market prices of various bio-based insulation materials to those of commonly used materials in France:

FIGURE 29: Market price (in €/m2 excluding VAT) of mineral, synthetic, and bio-based insulation materials in France in 2016



Source: Rabbat *et al.* (2022)

By contrast, in the US bamboo flooring costs around $24.21 per square meter on average, retail with a range of between $16.14 and $118.4 per square meter. In countries such as China where bamboo is grown in high volume, prices can be lower; some estimates say bamboo flooring costs about $12.40 per square meter to manufacture (UNCTAD 2022).

TABLE 26: Comparison of bamboo product prices in the US

Brands	Cost
Ambient Bamboo Floors	$3.29 – $4 per square foot
Cali	$3.50 – $6 per square foot
EcoFusion	$5 – $8 per square foot
Home Decorators Collection	$1 – $4 per square foot
Home Legend	$2 – $5 per square foot
Morningstar	$2 – $4 per square foot
Plyboo	$4.50 per square foot
Teragren	$6 – $8 per square foot
USFloors	$3 – $4 per square foot

Source: Gerhardt and Allen (2022)
Note: A square meter equals 10.76 square feet

Market dynamics

Drivers

The demand for green buildings is a macro-driver of the seaweed-for-construction industry. According to our interviewees, this demand for green building materials is coming from several areas as industry players embrace environmentalism. Large organizations – including social housing organizations and architecture firms – are seeking more sustainable materials for their building portfolios. This is coupled with increasing consumer interest in environmentally-friendly homes and bio-based materials. The public is increasingly aware of the health and environmental hazards of carbon emissions. At the same time, startups highlight how seaweed can decrease our dependence on wood, fresh water, and land while also fixing carbon. Because of this, seaweed material startups have reported a rise in inquiries from wholesalers, independent architects, contractors, and infrastructure companies expressing interest in entering potential partnerships.

There is particular interest from green architecture players in reducing the use of fossil-fuel-based plastics in construction. In 2021, SiteStak showed that the construction industry ranked as the second-biggest producer of waste plastic, after the packaging industry (SiteStak 2021). The biggest sources of this waste include construction inefficiencies on building sites, a steadily growing sector, and an overreliance on single-use plastics. Much of this waste ends up in landfills, in other countries, or in the ocean. Consequently, bioplastics are being explored as a renewable solution that could help reduce dependency on fossil resources, produce biodegradable and compostable products, and increase waste management efficiency. These green architecture companies are an important driver for the development and use of seaweed bioplastics.

In certain parts of the world, another driver is the tourism industry. In 2018, the Caribbean-wide cleanup of invasive *Sargassum* blooms cost $120 million, but this does not include decreased revenues from lost tourism (Galoustian 2021). Hotels and governments have been demanding solutions to resolve the economic impacts of this issue. In addition, the buildup of biomass impacts the environment by deoxygenating the water and suffocating coral reefs. To relieve the economic and environmental pressure created by these blooms, in 2015 BlueGreen Mexico began turning *Sargassum* into building blocks for houses. The first construction, Casa Angelita, used 2,150 SargaBlocks made from

20 tons of fresh *Sargassum*. Sargablocks come in two sizes: 30 x 15 x 12 cm and 40 x 15 x 12 cm and cost 10–12 pesos (about $0.42–$0.51) per block.

The development of enhanced processing and biorefining technology is also facilitating the growth of the seaweed-for-construction industry. Several innovators are leveraging this enhanced technology, including the startups Blu3 and MacroOceans. As outlined in the commonality section of the report (Chapter **xx**), this technology allows different components in seaweed to be applied to different sectors: fibrous materials and alginates are used in construction, while lipids are used in biofuels, and proteins in food products. The company Weedware, based in the Netherlands, is using biorefineries to process local European macroalgae. The team processes the biomass in a refinery tank with a 5,000-liter capacity, splitting the organism cells and extracting components such as polysaccharides and starches. The output is typically divided into three or four streams, from which liquid extracts are derived that can be used by certified organic farmers as natural biostimulants and to prevent waste. The remaining components of the biomass are used in a variety of products for the homeware industry through a process of mixing, blending, grinding, and extruding.

The potential to turn buildings and cities into carbon sinks is another important driver of the use of macroalgae technology. Many organizations and research groups, such as the Carbon Leadership Forum, are striving to accelerate change in the building sector to reduce and eliminate the embodied carbon in building materials and construction (Kriegh *et al.* 2021). The demand is significant. According to some forecasts, the potential of this idea is considered high, but there are also some challenges associated with it, such as the permanence of carbon sequestration. The general consensus is that we will likely see more of this trend in the coming years, although it is difficult to predict exactly what form it will take.

Competition

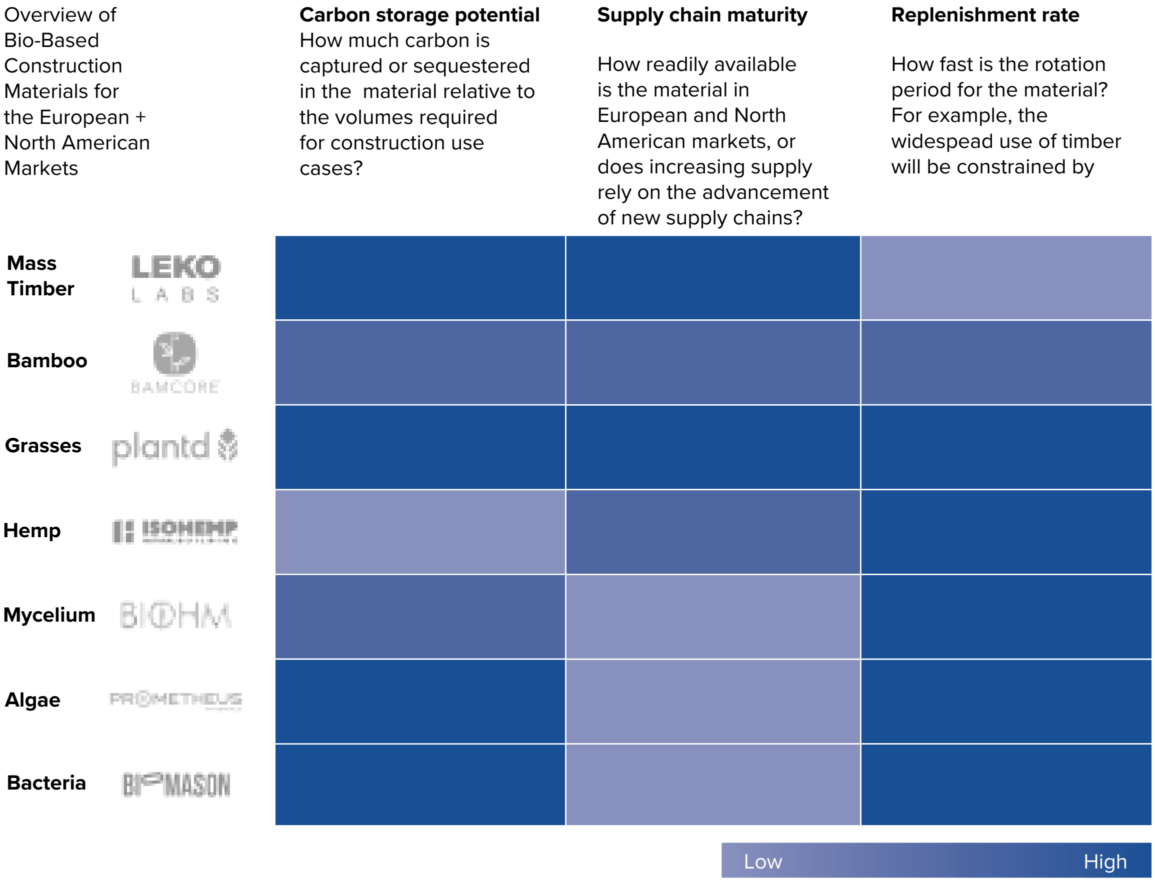
To move beyond niche applications, new biomaterials, including macroalgae-based products, must compete with concrete, timber, and plastic-based construction materials to have any impact at scale. Currently, cultivated seaweed-based products are not cost-competitive with these traditional materials. According to our primary research, cultivated temperate brown kelp species from China and South Korea sold for around $400–500 per ton fresh weight at the farm gate in 2022. Farm-gate prices for cultivated tropical red seaweeds started at around $300 per dry ton for *Gracilaria* and $500 per ton dry weight for Spinosum (*Eucheuma denticulatum*) in Indonesia (Seaweed Insights 2023). By comparison, in the EU, building blocks and bricks made of either cement, concrete, or artificial stone currently cost around $125/ton, while timber-based construction materials typically fetch less than $100/ton.

Nevertheless, there are cases where seaweed products show promise. As mentioned above, Sargablocks are made using wild seaweed. According to our interviewees and primary data, the 10–12 peso ($0.42–$0.51) cost per block is half the cost of adobe bricks made in Mexico. In comparison, a good rule of thumb is to expect bricks made in the US to cost $2.50–$3.00.

Many bio-based materials are already used as green construction materials globally, including wood, bamboo, and grasses/straw. Figure 30 compares the supply chain maturity, the carbon storage potential, and the replenishment rate of these materials. Algae-based materials have high storage potential and replenishment rate compared to alternatives, but supply chain immaturity is a major barrier to implementation (Kriegh *et al.* 2021). In addition, the true carbon storage potential of seaweed in buildings is unknown. Wood and grasses have high carbon storage potential and supply chain maturity, which supports their current leading position in the bio-based industry.

Compared to these materials, seaweed is an attractive alternative because it grows in the ocean. This means it can be used to relieve pressure on land use and freshwater resources. It also grows very quickly and, in the Caribbean, where invasive *Sargassum* is available in high volumes, it can be wild-harvested and incorporated into products at low cost.

FIGURE 30: Bio-based construction materials



Overview of Bio-Based Construction Materials for the European + North American Markets

Carbon storage potential How much carbon is captured or sequestered in the material relative to the volumes required for construction use cases?

Supply chain maturity

How readily available is the material in European and North American markets, or does increasing supply rely on the advancement of new supply chains?

Replenishment rate

How fast is the rotation period for the material? For example, the widespread use of timber will be constrained by

Source: AO Proptech (2022)

Challenges

Several challenges face the use of seaweed in green construction:

Higher costs: The use of seaweed construction materials is more costly than traditional processes. Several interviewees highlighted how expensive processing can be in terms of technology and highly skilled labor costs. This can be a barrier to the adoption of green construction, particularly for low-income housing projects.

Difficult-to-manage properties: Seaweed's properties, such as its tendency to absorb water and alter its shape and weight, can be difficult to work with. Deformation of biopolymers can be a challenge because in humid environments humidity levels affect the material and make it more pliable, but in dry conditions it becomes extremely stiff. In humid environments, whole seaweeds are also prone to rotting. To make seaweed a suitable exterior material, it is important to find a way to create hydrophobic films that can withstand different weather conditions.

Limited availability of sustainable materials: Few sustainable seaweed building materials are widely available. As mentioned in the commonalities section, this is attributed to the lack of seaweed supply. A focus on using locally grown seaweed species is quite important because it reduces the need for transportation over large distances.

Lack of clear industry standards: The green construction industry is still relatively new, and there are not yet established industry standards for sustainable building practices. Regulations vary between countries and can change rapidly. This can make it difficult for contractors and architects to know which methods and materials are truly sustainable in the long term. The acceleration of embodied-carbon laws will increase transition risk, and builders will likely pick the most widely accepted bio-material, which in most cases is timber. The lack of awareness regarding certified and regulated materials is another related challenge.

For entrepreneurs, policy changes can be challenging. Although some governing bodies hope to regulate all types of buildings, others are more selective and focus on specific characteristics – such as size, end use, or ownership structure. Different rules apply to residential and commercial buildings and, even within the commercial sector, there may be differences in standards for institutional and privately owned buildings. It can be costly for innovators to navigate policy changes without adequate support.

Industry's resistance to change: The construction industry is traditionally slow to adopt new technologies and methods. This can make it difficult to convince contractors and developers to switch to green construction practices. As a result, incorporating new materials into supply chains is a lengthy process. Scaling the use of green building practices and materials requires overcoming risk aversion in the architectural, engineering, and construction (AEC) sector, which also relies on a limited pool of specialized green construction skills (AO Proptech 2022). Projects are either very small or very large, with few in between. Consequently, the seaweed construction sector is currently focused on small- to medium-sized projects. However, to have a meaningful impact on climate change, large-scale production will be necessary.

Difficulty in measuring the benefits of green construction: It can be difficult to quantify the long-term benefits of green construction, such as reduced energy and water use. LCAs do not yet exist for many products in this sector and this can make it difficult to convince stakeholders to invest in green projects. There is a need to quantify the environmental impact of the processing operations required for the intended applications for construction (Rossignolo *et al*. 2022).

Lack of compositional studies: There is a gap in specific studies of the composition and behavior of seaweed in its different forms of application. The sector must undertake more studies using seaweed for construction.

Regulations

There is increasing demand for energy-efficient and environmentally-friendly new buildings. Decision makers in many countries are therefore focusing resources on controlling embodied carbon in new construction by encouraging bio-based buildings. In recent times, there has been an acceleration of embodied-carbon regulation in several economies, particularly in Europe and North America. The Danish government, for instance, has now demanded that all newbuilds require LCAs. It will also cap newbuilds with a floor space of more than 1,000 m^2 to a CO_2e limit corresponding to 12kg CO_2e/m^2/year (Passive House+ 2021). In addition, regulatory regimes worldwide are setting explicit targets for bio-based products. For example, starting in 2025, 25 percent of public newbuilds in France must be bio-based. By 2030, that percentage must reach 50 percent.

In the developed nations, enforcing these policies is expected to be stringent. Our interviewees underscored the significance of this shift in the regulatory compliance system toward greater strictness. Instead of offering support solely through carbon credits, emission-reduction incentives, and voluntary certification programs, it is expected that tough penalties for high emissions will be handed down in order to accelerate the transition to more sustainable practices. As a result, the traditionally conservative construction industry is recognizing the need to embrace more sustainable practices.

Market outlook

With increasing demand for construction, low-carbon, bio-based alternatives to materials like cement and concrete will be crucial in reducing emissions from this sector. Backed by favorable regulatory and technological developments, the bio-based construction market is expected to experience a CAGR of 10 percent between 2022 and 2030. The seaweed-based products market could be worth up to $1.4 billion by 2030. However, there are some potential deal-breaking challenges which have a low likelihood of being overcome – specifically, the need for high volumes of low-priced seaweeds.

According to our interviewees, the market for seaweed-based construction materials is expected to remain a niche market for the next 5–10 years. This is primarily due to cost competitiveness, which is a key influence on the buying decisions of larger corporations. Nevertheless, stakeholders expect significant growth in seaweed-based construction products over the next decade, driven by increasing regulatory pressures and changes in policy that are making sustainable building materials more attractive. Data reflect strong interest within the investment community in the development of bio-based materials. For example, investment in green construction materials experienced a CAGR of 84 percent between 2017 and 2022, reaching $2.2 billion in 2022, due in part to the acceleration of embodied-carbon policies (AO Proptech 2022).

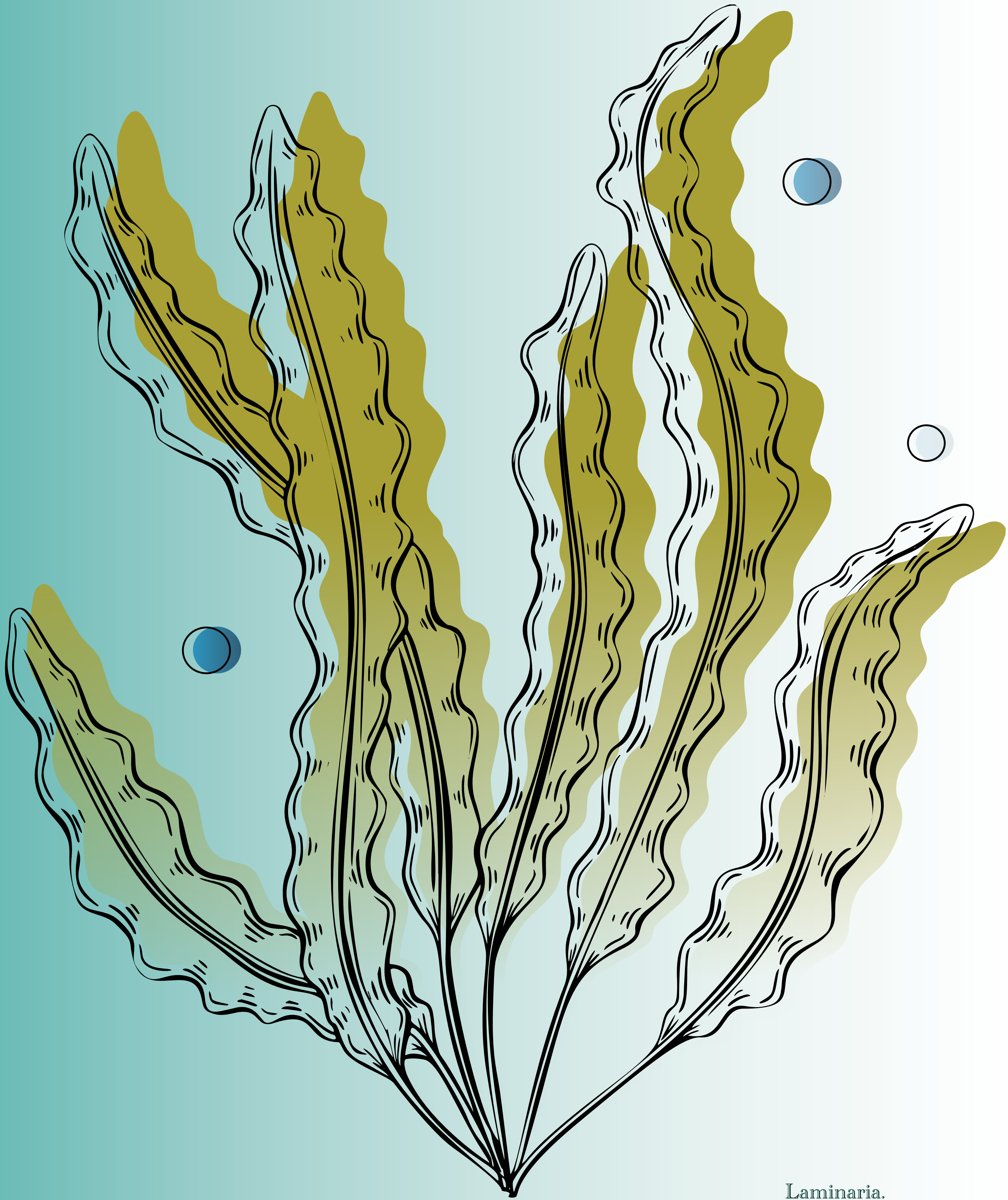
The widespread use of macroalgae in construction will require high volumes of biomass. A small house built from Sargablocks requires approximately 20 tons of wet seaweed. Using this much biomass in regions like Europe, where total farmed macroalgae amounts to much less than 1000 tons, is unfeasible Building larger buildings would require significantly more wet seaweed to have any impact on climate change. Currently, only a few companies exploring macroalgae-based construction materials are vertically-integrated aquaculture operators, meaning they will rely on strong relationships with farmers in the future. In emerging macroalgae locations, like Europe, a focus on collaboration is helping to gradually scale up macroalgae production. This relies on strong partnerships among seeding and propagation experts, farmers, and product developers, which will help to ensure that the quality and consistency requirements of the seaweed used in construction materials are met, and the cost of production remains competitive.

Developments in biorefinery technology are particularly promising for the sector. Biorefinery technology received the largest sum of investment in the seaweed sector in 2022 (Hermans 2023). Interviewees highlighted the importance of developing biorefineries and processing facilities locally to ensure that seaweed is harvested and used sustainably, instead of being shipped long distances. In this way, bio-based materials will meet LCA guidelines, which will increasingly be used to evaluate the sustainability of newbuilds. By prioritizing local production and consumption, the negative effects of mass production can be avoided, and the product can have a positive impact on the environment and the local community.

Many seaweed-based interior design products can be produced through injection molding. However, advances in various extrusion technologies are showing promise for the industry. For instance, small- and large-scale 3D printing that incorporates advanced robotic technology, allows teams to create more desirable products. Additive manufacturing is a 3D printing process, which builds parts, layer-by-layer, by depositing material according to digital, three-dimensional, design data. This allows for more efficient design, has fewer restrictions, and is faster than traditional fabrication processes. It also produces very little waste material, which helps reduce costs (Petruzzi *et al.* 2022).

Our interviewees highlighted the importance of taking a systems look at the supply chain, and asserted that funneling investment into scaling sustainable farming (see commonality section), harvesting, and building bigger biorefinery facilities close to farms will improve the sector's environmental footprint.

In developing seaweed regions such as Europe, investors need to focus on improving seaweed farming and the logistics and transportation of seaweed from farm to production facility. Several interviewees suggested that investing in stakeholder committees and cooperatives could be beneficial. This would mean that the industry could avoid some of the fragmented supply chains that have thus far restricted it, and that greater impact can be made. This approach will create a more organized, efficient, and sustainable macroalgae industry that can meet the increasing demand for sustainable building materials.



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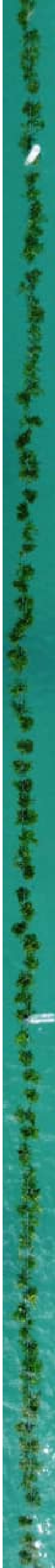


5

ECOSYSTEM SERVICES

Key highlights

Ecosystem Services

Outlook: Provisioning services are the current main focus for seaweed cultivation. However, macroalgae provide a range of other benefits, including regulating and supporting services which have not been fully commercialized or leveraged. Many organizations have submitted proposals for blue carbon credits using seaweed. Based on this, it is possible that internationally recognized credit certifications for blue carbon seaweed projects will be available by 2025.

The scaleup of land-based bioremediation operations is expected by end of 2024, and more attention is shifting toward the bioremediation potential of ocean farming and macroalgae-based, integrated, multi-trophic aquaculture (IMTA).

Several stakeholders interviewed suggested that biodiversity enhancement could become one of the more important ecosystem service attributes of seaweed farming and restoration from 2023 to 2033. Nevertheless, there are some critical challenges to address for these applications, including insufficient measuring, reporting and verifying; lethargic certification procedures; a lack of public awareness; a lack of consensus among scientists; and poor alignment between scientists and industry.

Introduction

Ecosystem services refer to the benefits that people obtain, directly or indirectly, from ecosystems (Clark *et al.* 2021). They can be divided into four categories: provisioning, regulating, supporting and cultural services (see Table 27).

TABLE 27: Four types of ecosystem services

Type of service	Definition and examples
Provisioning services	Material benefits produced by natural ecosystems and are extracted directly from nature to meet basic human needs. Examples are food crops, trees, fish, livestock, water, fuelwood, fodder, fur, latex, natural gas, and plant fiber that can be made into textiles.
Regulating services	Benefits provided by ecosystem processes that moderate or regulate natural ecological phenomena and, by so doing, keep ecosystems clean, functional, resilient, and sustainable. Examples are the cleaning of the air by plants, the decomposition of wastes by bacteria, the pollination of flowers and fruit trees by bats and insects, the protection of soil against erosion by tree roots, the uptake of pollutants, climate regulation via carbon sequestration, and shoreline protection offered by natural resources like mangrove forests which reduce erosion and absorb storm surge impacts during extreme weather events.
Cultural services	Non-material value and benefits that individuals and society derive from ecosystems, and which enhance their cultural advancement. Examples include hiking, swimming, and other forms of recreation, wildlife viewing, ecotourism, creative inspiration, spiritual reflection, and other aesthetic experiences.
Supporting services	Underlying functions and processes provided by the natural world that serve as the foundation for the other three kinds of ecosystem services and make them possible. Examples are photosynthesis, tree growth, nutrient cycling, conservation, soil creation, the water cycle, water storage, flow regulation, groundwater recharge, and habitat provisioning.

Source: Adapted from Clark *et al*. (2021)

The main ecosystem-related focus for seaweed cultivation is that it creates provisioning services. However, cultivated and wild macroalgae provide a range of other ecosystem benefits, including regulating and supporting services which have not been fully commercialized or leveraged (see Figure 31). These can help unlock additional value from the sector and could be crucial for accelerating the growth of the global seaweed industry.

FIGURE 31: Ecosystem services provided by seaweed (source KFF)

This chapter discusses the challenges and opportunities in seaweed-based ecosystem services, with a particular focus on blue carbon, bioremediation, methane reduction, and biodiversity enhancement – areas of heightened interest in the sector. Unlike previous chapters, this chapter takes on a case study format. By highlighting early success stories from projects in these areas, it will explore how these ecosystem services are being valorized and whether they are likely to play a significant role in the seaweed sector in the coming decade. Market outlooks were based on stakeholder interviews and on an analysis of the available literature.

5.1. Capitalization of ecosystem services

In a recent report, van den Burg *et al.* (2022) identified and evaluated mechanisms for capitalizing ecosystem services provided by seaweed aquaculture. Six leading payment mechanisms are highlighted in Table 28:

TABLE 28: Leading payment mechanisms

Payment mechanism	Description
Charging aware consumers price premiums	In this mechanism, consumers pay the costs via price premiums on final products. This would require consumer awareness of the provision and importance of ecosystem services provided by the company. Awareness can be fostered through various methods, including effective eco-labeling.
Trading credits for ecosystem services	Tradeable credits for ecosystem services can be traded business-to-business, and can be generated by seaweeds that capture or remove particles and nutrients from the water as well as sequester carbon. These credits can be sold on voluntary markets.
Creating the social license to produce seaweed	Social license refers to the level of public trust granted to a corporate entity or industry sector by the community at large and by its key consumer base. Under this mechanism, seaweed farming can help overcome negative sentiment toward other ocean operations, for example, wind and aquaculture farms. This can include supportive regulation to enable co-location of aquaculture on offshore wind farms or the production of lower-trophic species as an alternative to using natural coastal systems for seafood production.
Providing subsidies for achieving positive impacts	Subsidies can be provided to the users of seaweed applications – for example, governments can subsidize the use of methane-reduction supplements.
Paying ecosystem services producers through taxes	Producers of lower-trophic species can be paid for the ecosystem services provided through general taxes collected from consumers or businesses.
Sharing the costs of production among beneficiaries	The costs of producing lower-trophic species are partially paid for by other beneficiaries of the ecosystem services provided. Cost-sharing can be between businesses or via targeted tax schemes. For example, fisheries have the potential of benefiting from seaweed cultivation due to an enriched or more biodiverse ecosystem resulting from habitat support services.

Source: adapted from van den Burg *et al.* (2022)

5.2. Blue carbon

In recent years, blue carbon – the carbon sequestered by coastal and ocean ecosystems – has drawn international attention because of its potential role in tackling the climate crisis. For example, in 2021, Macreadie *et al.* described how large-scale restoration and protection of blue carbon ecosystems (BCEs) could draw down more than 1,000 teragrams of carbon dioxide equivalents ($TgCO_2e$) per year by 2030, equivalent to about 3 percent of global emissions. Compared to the high cost of many technology-led climate solutions, BCEs have been proposed as a cost-effective, scalable, nature-based climate solution (Macreadie *et al.* 2021).

BCEs are gradually being integrated into verified carbon-offset methodologies and voluntary markets. Certified methodologies for BCE restoration, such as the Verified Carbon Standard methodology for tidal wetland and seagrass restoration (VM0033), have allowed multiple restoration projects to receive capital from large organizations such as Apple (Apple Newsroom 2019). In return, these corporations can offset their emissions. The heightened demand for blue carbon offsets, serviced by voluntary carbon markets, provides the principal route to valorizing this ecosystem service.

BCEs generally refer to mangrove forests, seagrass meadows, and tidal marshes. However, scientists have recently explored the inclusion of seaweed in blue carbon markets. This stems from seaweed's rapid growth rate and very high CO_2 absorption capacity (Macreadie *et al*. 2021). The carbon uptake of seaweed is called net primary production (NPP), and multiple studies have shown how a portion of that carbon can eventually become permanently sequestered in ocean sediments. Multiple reports have now confirmed the potential of this carbon fixation pathway. Krause-Jensen and Duarte (2016), for instance, explained how macroalgae can sequester large stocks of organic carbon in deep ocean environments and coastal sediments. This can occur via macroalgal material drifting through submarine canyons or the sinking of negatively buoyant macroalgal detritus. Globally, their estimates indicate that wild seaweed might sequester hundreds of millions of tons of carbon per year.

Additional carbon experiments conducted in Australia estimate that the country's kelp forests sequester more than 30 percent of the total blue carbon sequestered by Australia's marshes, mangroves, and seagrass beds (Filbee-Dexter 2020).

There are several routes by which seaweed can sequester carbon or mitigate emissions (see Table 29).

TABLE 29: Routes to sequestering carbon or mitigating emissions through seaweed

Deep ocean sequestration	Macroalgae (pre- or post-processing) are sunk into the ocean to depths of over 1000 meters. At these depths, the macroalgae can be sequestered for hundreds to a few thousand years if they demineralize in the deep ocean, or for thousands to- millions of years if they are buried in marine sediment. (Ocean Visions 2023).
Sediments	Fragments of seaweed detach during the growing period and become sequestered in sediments.
Carbon export	Fragments of seaweed detach and are naturally exported into the deep sea.
Seaweed products	CO_2 emissions are avoided when seaweed-based products replace conventional, emissions-intensive products or carbon is sequestered on land through land-based carbon dioxide removal products (for example, biochar).

Source: Adapted from United Nations Global Compact (2021)

Based on this carbon reduction potential, seaweed farming, the harvesting of free-floating algae, and the restoration of kelp ecosystems have all been proposed as potential routes for carbon removal and sources of blue carbon credits. In this chapter, we highlight blue carbon case studies that are leveraging both wild seaweed resources and seaweed aquaculture.

The potential scale and relatively low cost of seaweed cultivation compared to kelp forest restoration makes it a particularly attractive route to carbon sequestration. Traditional seaweed aquaculture is typically limited to coastal areas that are protected from storms and waves, which reduces the amount of space available for farming. According to some of our interviewees, this reduced space falls short of the scale needed for remove enough CO_2 to affect climate change. A range of new culture techniques are being explored to allow farms to expand from a few hectares to thousands of hectares in the offshore environment. Known as open ocean afforestation, it is still in the early stages of development, but organizations like Climate Foundation claim to have achieved technology readiness level 7 (TRL7). This level refers to a system model or prototype demonstration in an operational environment.

Methods for measuring carbon sequestered by seaweed can be grouped into three categories: monitoring carbon uptake, monitoring carbon permanence, and analyzing carbon capture (Rose and Hemery 2023). There is no overall consensus on which is best, but forensic carbon accounting has been proposed as a thorough methodology. Regardless, the calculation of the amount of blue carbon in seaweed bed ecosystems can be performed by multiplying the area of the target ecosystem by the absorption coefficient. In seaweed bed ecosystems, organizations can calculate absorption coefficient by multiplying "wet weight per unit area" by the "blue carbon residual rate."

Pricing methodologies vary, depending on the route taken to sequestration. For pathways that involve the restoration of seaweed bed ecosystems, blue carbon credits can reach relatively high prices. For example, according to some interviewees, in 2022 blue carbon credits issued in Japan (which would include Urchinomics' blue carbon credits) averaged JPY 78,063/ton ($573/ton) of CO_2 removed, versus JPY 72,800/ton ($534/ton) in 2021. However, these prices are very high compared to the global average. Several reports indicate that credits for blue carbon projects in Asia and Central America are being offered for about $13–$35 per ton of carbon removed. According to Bloomberg, in January an offset traded at $7.53 a ton.

Howell (2022), citing a new report from McKinsey (Claes 2022), states that the estimated cost of carbon sequestered per hectare of ocean area with farmed seaweed is around $200–$300 per ton of CO_2 abated. Meanwhile, DeAngelo *et al*. (2023) submit that removing CO_2 via deep-sea seaweed sinking can be expected to cost a minimum of $480 per ton of CO_2, which is high compared to the current prices of other carbon offset methods.

TABLE 30: A selection of case studies investigating seaweed in blue carbon strategies

Route to carbon reduction	Example organization (HQ location)	Description	Recent milestones
Macroalgae cultivation/ open ocean afforestation/ carbon export/ deep ocean sequestration/ seaweed products	Running Tide Technologies (US)	Besides multiple carbon removal technologies, this startup is developing a nature-based system for removing carbon from the atmosphere using macroalgae. Kelp "seeds" are grown on compressed wood-and-limestone buoys and released into the open ocean around Queensland and New South Wales, Australia where they sink deep, storing the embodied carbon away for centuries. The company is also building a data-rich platform and measurement, reporting, and verification (MRV) tools to track and optimize the system.	• Is nearing commercialization of ocean alkalinity enhancement. • Aims to commercialize macroalgae-based carbon removal technology within 18–36 months. • Has made significant strides in advancing macroalgae production technologies: including how to efficiently seed the seaweed onto substrates. • Employs machine vision and advanced measurement techniques to optimize processes, and is currently making these tools ready for commercialization.

(Table Continued)

TABLE 30: ***Continued***

Route to carbon reduction	Example organization (HQ location)	Description	Recent milestones
Macroalgae cultivation/ open ocean afforestation/ carbon export/ seaweed products	The Climate Foundation (US/Australia)	This project aims to develop a regenerative, climate-positive marine economy while measuring carbon export. The organization hopes to provide food security, sustainable livelihoods, ecosystem regeneration, and carbon balance. For this, they are using marine permaculture – setting up irrigation platforms that provide a deep-water floating substrate with deep cycling – which involves lowering and raising submersible seaweed platforms for access to nutrients and sunlight. For revenue, the project aims to generate seaweed products, including fertilizers, and eventually access carbon credit markets.	• The organization stated that the installation of deepwater seaweed farms was successful and the biodiversity boost has attracted fish, squid and fishermen. • Is currently collecting and growing different strains of local seaweed To learn the biological response in offshore farming. • Winner of XPRIZE's $1 million carbon prize. • Currently in phase 3 (TRL 7 or 8) of a 4-phase project. Just launched a 1,000 cm^2 platform. In late 2023, the foundation is launching a hectare scale platform.
Macroalgae cultivation/ open ocean afforestation/ carbon export/ deep ocean sequestration/ seaweed products	SINTEF, DNV, Equinor and Aker BP (Norway)	This project looks to cultivate large volumes of sugar kelp on long ropes connected to buoys set out to sea. The team is investigating storage of biomass on the ocean floor: harvested kelp will be sunk to the ocean floor in areas deeper than 1,000 meters. Also developing long-lifetime carbon products, including biochar.	• The "Seaweed Carbon Solutions" project officially began in April 2022. • The project has implemented a coupled, 3D, hydrodynamic-biogeochemical-kelp model system (SINMOD) to assess the cultivation potential of kelp in various coastal locations in Norway (nearshore and offshore) and to optimize kelp production. • The commercial scaling-up phase will begin in 2025 at one or more sites off the coast of Trondelag in central Norway, and will run through the end of 2024.

(Table Continued)

TABLE 30: ***Continued***

Route to carbon reduction	Example organization (HQ location)	Description	Recent milestones
Macroalgae cultivation/ sediments	OCEANS 2050 (France)	The organization has been quantifying carbon sequestration in soft sediments beneath existing seaweed farms. They are examining 21 farms in 12 countries on 5 continents, using the abundance of lead-210 (210Pb) in the sediments to calculate sequestration rates. The goal is to produce a protocol for certifying carbon sequestration beneath existing macroalgae farms to allow the farmers to generate revenue from voluntary carbon markets. VERRA will be the certifying body.	• The research found that the average amount of carbon sequestered per hectare per year was 1.4 tons, although this varies widely: ranging from 0 to 8 tons. • Submitted methodology for blue carbon certification to VERRA.
Macroalgae cultivation/ sediments and carbon export	Kelp Blue and Kelp Forest Foundation (KFF) (Namibia)	KFF aims to quantify ecosystem services of giant kelp (*Macrocystis*). This initiative is designed to create a methodology to validate and monetize the carbon sequestration impact of permanent (that is, non-harvested) giant kelp afforestation.	• Kelp Forest Foundation's entry, in collaboration wiatissimure and Kelp Blue, was selected as one of eight winners of MIT Solve 2022. • Submitted draft methodology for blue carbon certification to Gold Standard.
Environmental subsidy/ macroalgae cultivation	GreenWave (US)	GreenWave replicates and scales regenerative ocean farms to create jobs and protect the planet. The team trains and supports ocean farmers, working with coastal communities around the world to create a blue economy. The Kelp Climate Fund is a subsidy that provides direct payments to farmers for the climate-positive role of their ocean farms, including carbon and nitrogen removal and habitat restoration. In return, farmers provide key monitoring data on out-planting, growth rates, and harvest yields to measure ecosystem services, increase production output, and establish infrastructure for farmers to "harvest" data and carbon credits.	For the 2022–2023 farming season, GreenWave has increased the budget for the Kelp Climate Fund to $310,000 and opened the application process to all North American seaweed producers who grow over 1,000 feet of kelp seed. This expansion has led to an increase from 9 to 39 farms across the country, with a total of 517,260 feet of seedstring expected to be planted. GreenWave plans to continue expanding the fund over the next five years until the annual seed subsidies reach $1 million, enabling 250 farmers to plant 1 million feet of kelp seed. At this scale, the fund is projected to support minimum annual carbon removal of 100 tons. GreenWave has also launched a blue carbon project to develop a kelp carbon credit protocol for certification by international carbon credit agencies.

(Table Continued)

TABLE 30: ***Continued***

Route to carbon reduction	Example organization (HQ location)	Description	Recent milestones
Kelp forest restoration	Urchinomics (Netherlands)	Urchinomics removes overgrazing sea urchins to try to turn barren seafloors back into kelp forests.	On November 21, 2022, Urchinomics secured the world's first voluntary blue carbon credit for kelp restoration. It was certified by the Japanese government.
Kelp forest restoration	Marine Restoration Program (South Korea)	Wild seaweed forests have been severely damaged along Korean coasts because of algal whitening events. In 2009, the Ministry of Oceans and Fisheries launched the Sea Forest Development program to prevent their further destruction (Sondak and Chung 2015).	Between 2009 and 2019, the Korean government invested about $280 million in reforestation efforts. In total, over 7,600 hectares of seaweed forests have been established on Jeju and over 8,300 hectares in the East Sea, totaling 21,500 acres of seaweed forests restored over a period of 11 years (Hwang *et al*. 2020).
Removing harmful algal blooms/ deep ocean sequestration	SOS Carbon (Dominican Republic)	A patent-pending technology for sequestering *Sargassum* in the ocean.	Has proven its hardware for cost-effective harvesting over the last two years. It has been operating commercially in the Dominican Republic and recently expanded to Antigua and Barbuda for wild harvesting.
Removing harmful algal blooms/ macroalgae cultivation/ open ocean afforestation/ carbon export/ deep ocean sequestration/ seaweed products	Seaweed Generation (UK)	Seaweed Generation has developed two main technologies: CO_2 removal using a robot called the AlgaRay, and cultivation with a system called Alga Vita. Project AlgaRay intercepts and sinks *Sargassum* for CO_2 removal.	The AlgaRay is in the early stages of automation and the startup has achieved remote-driving capabilities. Is launching a pilot in Antigua to intercept and process *Sargassum* in the spring. The pilot will allow them to test the technology and conduct measurements, verifications, and monitoring to understand the carbon content of the *Sargassum*. -Recently raised $1.3M to finance the company.
Removing harmful algal blooms/ seaweed products	Woolly Rock Rose (UK)	Woolly Rock Rose aims to track, harvest, and use *Sargassum* in a multitude of products via a regenerative business model, creating sustainable livelihoods for those most impacted by the blooms and revitalizing the local economies and communities in which it operates.	Has received interest from other countries and created a concept note for a Caribbean nation facing different challenges with *Sargassum*. The UK Department of International Trade has also asked the startup to host an event promoting *Sargassum* solutions in the Dominican Republic.

5.3. Seaweed bioremediation

Bioremediation involves using biological organisms under controlled conditions to degrade, neutralize, or remove harmful contaminants from an area. Both freshwater and marine macroalgae can be used in this way in land-based aquaculture facilities or in open-water ocean farms (see Table 31). The seaweed is grown in polluted or eutrophic water, harvested, and removed from the system it is grown in. This can help remediate nutrient pollution, particularly nitrogen and phosphorus pollution that results from the overuse and runoff of commercial fertilizers into coastal waters, or direct discharges from nutrient-intensive industries such as wastewater treatment plants. In addition, seaweed can be used for wastewater treatment and bioremediation around aquaculture sites (for example, for salmon or shrimp farming) to help prevent eutrophication, which can cause harmful algal blooms and dead zones.

Bioremediation-focused, commercial seaweed cultivation is mostly performed in land-based systems for point-source pollution, which originates from a single location. For example, abalone farms in South Africa have been using *Ulva* for ammonia removal in abalone effluent since 2002 (Clark *et al*. 2021). Integrated multi-trophic aquaculture (IMTA) of land-based *Ulva* and abalone farms allows for partial recirculation of the water, reduced pumping costs, increased abalone productivity, and a reduced environmental footprint (Clark *et al.* 2021). Ultimately, this application of seaweed can provide the farmer with an economic benefit by reducing production costs and increasing the yields of the primary aquaculture target (Clark e*t al.* 2021).

Assimilation of nitrogen and phosphorus using ocean-based seaweed farming (not primarily focused on bioremediation) and IMTA has also been investigated at length. According to Seaweed for Europe, by 2030 the European seaweed industry could remove 6,000–20,000 tons of nitrogen and 600–2,000 tons of phosphorus from coastal waters every year (Vincent, Stanley, and Ring 2020). This would significantly improve marine water quality. Nutrient removal at this scale would be equivalent to removing 2–6 percent and 4–13 percent of the estimated anthropogenic nitrogen and phosphorus, respectively, that entered the Baltic Sea in 2014 (Vincent, Stanley, and Ring 2020). For comparison, Chinese seaweed aquaculture removes approximately 75,000 tons of nitrogen and 9,500 tons of phosphorus annually (Xiao *et al*. 2017).

One way this ecosystem service can be valorized is through the use of credit markets. Although not applied to seaweed, in Australia, the Great Barrier Reef Credit Scheme is a market-based solution that aims to improve water quality in the reef. Land managers generate a tradeable unit of pollutant reduction known as a “Reef Credit” by implementing projects that reduce nutrients, pesticides, and/or sediments.

In general, pollution uptake can be quantified by measuring the concentration of nutrients in the seaweed tissue and multiplying these by the harvested biomass. To estimate the nitrogen content of each farm’s crop, GreenWave multiplies dry-weight values of farmed seaweed by 2 percent, resulting in pounds of nitrate removed (GreenWave n.d.). Similarly, The Seaweed Company states that every ton of seaweed harvested has absorbed 120kg of CO_2, 2kg of nitrogen, and 0.2 kg of phosphorus (The Seaweed Company 2023). The recovery value of nutrients can be calculated from wastewater treatment facilities, which are $10–30/kg nitrogen and $4/kg phosphorus (Chopin and Tacon 2021). According to Costa-Pierce and Chopin (2021), the economic value of nutrient bioremediation services provided by the world’s seaweed aquaculture production is between $1.1 billion and 3.4 billion for nitrogen and $51.8 million for phosphorus (Costa-Pierce and Chopin 2021).

In addition, converting seaweed into end products allows the recycling of these nutrients, creating a circular bioeconomy. This is particularly important in the case of phosphorus, which is a finite resource. Developing seaweed into end-use products such as fertilizer replacements supports resource efficiency and helps create a circular economy for phosphorus use.

TABLE 31: A selection of case studies investigating seaweed in bioremediation strategies

Route to Bioremediation	Organization (HQ Location)	Description	Recent milestones
Macroalgae cultivation land-based bioremediation	Pacific Bio (Australia)	The company's technology, RegenAqua, uses macroalgae to strip wastewater of environmentally harmful pollutants that municipal wastewater treatment plants and aquaculture farms create before they enter the ecosystem. This technology is then used to create nutrient-rich products for plants and animals.	Pacific Bio recently raised $3.5 million in a friends-and-family round. This year, they hope to increase their revenue to over $15 million. Pacific Reef Fisheries, a major producer of sustainably farmed black tiger prawns in North Queensland, is their primary source of revenue and produces more than 1,000 tons annually (LaFrenz 2022).
Macroalgae cultivation land-based bioremediation	AgriSea (New Zealand)	AgriSea is working with the University of Waikato on an *Ulva* growing trial in Kopu marine precinct in the Coromandel. The seaweed will be used to remediate the nutrients that freshwater plants are currently unable to absorb.	The New Zealand government, through the Ministry of Primary Industries' Sustainable Food and Fibre Futures Fund, is contributing almost $453,000 to cultivate *Ulva* in three ponds, totaling 60 square meters.
Macroalgae cultivation land-based bioremediation	Aqua Curo (New Zealand)	Aqua Curo is a long-term trial in harnessing bioremediation to remove New Zealand's most common pollutants from wastewater.	Aqua Curo has partnered with the University of Waikato and Western Bay of Plenty District Council to develop the largest alternative water treatment facility in the southern hemisphere. The pilot trial in the Bay of Plenty has yielded positive results (BOP Business News 2022).
Macroalgae cultivation coastal bioremediation	GreenWave (US)	As mentioned in Table 18, GreenWave's model is deployed to restore ocean ecosystems, capture blue carbon and nitrogen, and support commercial farming. GreenWave's Kelp Climate Fund is a subsidy for ocean farmers to support a bundle of environmental impacts, including carbon, nitrogen, and reef restoration.	GreenWave's Kelp Climate Fund hopes to reach annual seed subsidies of $1 million. At this scale, the fund is projected to support minimum annual nitrogen removal of 8 tons.
Macroalgae cultivation coastal bioremediation	Australian Seaweed Institute (Australia)	The solution involves deploying a network of cultivated seaweed biofilters in targeted locations across the Great Barrier Reef catchment that will remove nitrogen and CO_2 loads that are damaging coastal ecosystems and the Reef.	ASI plans to have seaweed biofilters operating at scale within the next 10 years. This includes developing 15,000 hectares of seaweed to significantly address the nitrogen problem and help protect the reef. ASI will conduct field trials in 2023 and aim for proof of concept by 2024. The company is aiming to scale up commercially, begin selling seaweed products, and start claiming nitrogen credits by 2025.

5.4. Methane reduction

A further ecosystem service provided by seaweed products is methane reduction in farmed animals. Studies have shown that macroalgae, such as *Asparagopsis taxiformis*, can reduce methane (CH_4) emissions from ruminants. This has motivated startups to pursue methane reduction supplements using seaweed. And – if emission credit schemes are expanded to include enteric methane emissions from ruminants – this would open a revenue stream for farmers. This application is explored in detail in the methane-reducing feed supplement chapter, but is highlighted here for comparison with other provisioning, supporting and regulating ecosystem services.

TABLE 32: A selection of case studies investigating seaweed in methane-reducing supplements

Route to methane reduction	Organization (HQ Location)	Description	Recent milestones
Licenser	FutureFeed (Australia)	FutureFeed exists to support the use of *Asparagopsis* as a natural ingredient for livestock to significantly reduce carbon emissions. FutureFeed owns the rights to the patents for using *Asparagopsis* as a methane-reduction additive. The company has licensed its technology to several teams around the world.	Over the past 24 months, FutureFeed has licensed its technology to 9 businesses in Australia, New Zealand, the US, Europe and Canada.
Land-based macroalgae cultivation/ methane-reduction supplements	CH4 Global (US)	CH4 Global is developing international *Asparagopsis* farms to reduce methane emissions from ruminant livestock.	In June 2021, the company made its first commercial sale of *Asparagopsis*-based cattle feed supplements in Australia. It is now building a large-scale, commercial production plant (EcoPark) for *Asparagopsis* in New Zealand.
Land-based macroalgae cultivation	Symbrosia (US)	Symbrosia is a Hawaii-based startup that reduces methane emissions using *Asparagopsis*.	Symbrosia recently partnered with Carman Ranch, a leader in regenerative agriculture, and with Neutral Foods, America's first carbon neutral foods company. The company raised $7 million in 2022.
Ocean-based macroalgae cultivation	Greener Grazing (Vietnam)	Greener Grazing's goal is to provide the necessary knowledge and tools to begin large-scale farming of *Asparagopsis taxiformis* in the ocean and assist producers in quickly building a supply.	Greener Grazing has successfully developed techniques to create, harvest, and seed vital spores for ocean-based farming. Unlike other startups, this organization is growing *Asparagopsis* through its complete lifecycle in the ocean.
Ocean-based macroalgae cultivation	Alga Biosciences (US)	Alga Biosciences uses a low-cost chemical process to create a kelp-based *A. taxiformis* equivalent.	The company has been exploring opportunities for large-scale seaweed farming in Iceland, Vietnam, and other parts of Southeast Asia.
Land-based and ocean-based macroalgae cultivation	Sea Forest (Australia)	Sea Forest is the first company in the world to cultivate *Asparagopsis* on a commercial scale through both marine and land-based aquaculture.	The company has invested more than $20 million in developing infrastructure as it gears up for commercial production of feed supplements to help reduce methane emissions from ruminant livestock.

5.5. Seaweed for biodiversity and wider ecosystem services

According to research by the World Economic Forum, over 50 percent of the world's GDP is generated by industries that are highly ($13 trillion) or moderately ($31 trillion) dependent on nature (Russo 2020). There are estimates that implementing nature-positive policies could generate more than $10 trillion in new annual business value and 395 million new jobs by 2030 (Lazard 2022). Seaweed offers several nature- and climate-positive benefits, including coastal protection and the enhancement of biodiversity through habitat provisioning. Among these nature-positive benefits, biodiversity enhancement is particularly promising and is gaining recognition from environment-focused investors.

Seaweed ecosystems provide a habitat for living marine organisms. Organisms can be attracted by the food, or shelter of kelp forests. There is some evidence suggesting that seaweed farms positively affect ecosystems by providing additional food and habitats, although much more work is needed to verify these accounts. In recent years, habitat provisioning and biodiversity enhancement from macroalgal cultivation has been evaluated on a local scale using a variety of approaches, including cameras and eDNA sampling. These measurement projects could enable the valorization of these services through payment schemes such as credit markets.

TABLE 33: A selection of case studies investigating seaweed for biodiversity and habitat provisioning

Ecosystem Services	Organization(s)	Description	Recent Milestones
Macroalgae cultivation/ seaweed products/ measuring biodiversity	Kelp Blue/KFF/ NatureMetrics	NatureMetrics is a world-leading provider of biodiversity monitoring data. The company is using environmental DNA (eDNA) surveys and metabarcoding in collaboration with several teams to understand biodiversity enhancement using seaweed cultivation.	1. NatureMetrics is collaborating with the Blue Marine Foundation's Sussex Kelp project to gather important eDNA baseline data for monitoring and tracking changes in the biodiversity of recently protected kelp forests. 2. NatureMetrics have an ongoing partnership with Kelp Blue and the Kelp Forest Foundation and are currently working on the Kelp Blue Namibian Project. The collaboration seeks to monitor the increase in biodiversity resulting from the establishment of a pilot offshore kelp farm in Namibia. The initial focus includes using eDNA to assess the impact of this type of mariculture on biodiversity. They are also working together to create assays and products to determine whether, and to what extent, the kelp farm is contributing to carbon sequestration in ocean sediments.

(Table Continued)

TABLE 33: ***Continued***

Ecosystem Services	Organization(s)	Description	Recent Milestones
Macroalgae cultivation/ seaweed products/ measuring biodiversity	Cascadia Seaweed	Cascadia Seaweed is the largest kelp cultivator in Canada. It was recently awarded $1.335 million from the British Columbia Salmon Restoration and Innovation Fund (BC SRIF) to plant 3.5 hectares of seaweed to study the relationship between kelp farms and fish biodiversity.	1. Cascadia has built 21 KelpCams that help monitor the farms for salmon and other fish. Beyond this, remotely-operated vehicles (ROVs) and divers have been used to survey and evaluate fish communities in the farms (Johnson and Bates 2022).
Ecosystem services impacts of seaweed farming	GreenWave Aotearoa (New Zealand)	EnviroStrat is leading a three-year, regenerative, ocean-farming pilot (in collaboration with GreenWave) to establish a seaweed supply chain in New Zealand.	1. The CO_2, nutrient, and biodiversity impacts of farming *E. radiata* are being measured over a three-year period. This includes identifying the biodiversity benefits from the co-location of mussels with seaweed farms. 2. EnviroStrat is adapting the Kelp Climate Fund concept developed by GreenWave to enable its seaweed farmers to receive monetary compensation in recognition of the environmental benefits being generated.
Kelp forest restoration and protection/ seaweed products/ measuring biodiversity	Kelp Forest Alliance	Kelp Forest Alliance is a collaborative initiative that brings together people and organizations to enhance, protect and restore kelp ecosystems.	1. Launched and created a platform for collaboration and tracking restoration. Mapped out 500 people working in this area. 2. Launched a kelp restoration guidebook which showcases the methods and feasibility of restoration projects. 3. Launching a target of 1 million hectares of kelp restored and 3 million hectares protected by 2030.

Seaweed farming can also provide cultural ecosystem services that significantly enhance the quality of life for coastal and rural communities. When combined with processing, there is potential to create inclusive value chains that benefit local people. In emerging nations, women have played a significant leadership role in the growth of the seaweed industry. Numerous case studies have demonstrated how the sector has greatly aided women's empowerment in ocean communities (Msuya and Hurtado 2017). Additionally, seaweed farming offers opportunities for diversifying sources of income, particularly for commercial fishermen facing job insecurity because of declining fish stocks.

5.6. Challenges for ecosystem service applications

There are multiple challenges that need to be addressed before macroalgae cultivation can be integrated in ecosystem service credit or payment frameworks.

TABLE 34: Challenges facing the incorporation of seaweed into blue carbon, bioremediation, biodiversity, and wider ecosystem service markets

Technical and scientific challenges
1. There is a pressing need for more effective tools to track the effects of macroalgae on ecosystems and gather data for informed decision-making. Interviewees highlighted how difficult this can be because the impacts of ecosystem services can vary greatly from location to location. 2. Estimates of the effect of climate change on macroalgae stocks are inadequate. Climate change affects marine systems through changes in temperature, pH, and salinity. There is a need to better understand how macroalgae will be affected by these changes. 3. There is disagreement in the science community on the validity and permanence of solutions due to the lack of measurement, reporting, and verification (MRV) when using seaweed for carbon removal. 4. Still too few case studies showcasing (with data) how macroalgal management can positively contribute to carbon sequestration, biodiversity, and nutrient remediation. 5. The scale required for seaweed to completely or significantly offset carbon emissions or absorb nutrients may be too large to achieve realistically. 6. Large-scale seaweed farming may have unintended negative effects, for example, on nutrient levels (for instance, in regions without excessive nutrients runoffs) or wild seaweed ecosystems (for instance, in areas where a lot of seaweed is farmed). There is also high uncertainty or disagreement around the deep-ocean sinking of seaweed and the risk of unintended impacts. 7. There has been insufficient investment in decarbonizing farming and processing operations that would reduce scope 1 and 2 carbon emissions. Scope 1 emissions are direct emissions from company-owned and controlled resources. Scope 2 emissions are indirect emissions from the generation of purchased energy, from a utility provider. 8. There are not enough life cycle analyses publicly available to make it possible to determine the true emission reduction potential of seaweed products.
Management, policy, legal, finance, social and business challenges
1. There is a lack of standardization among the certification processes for the emissions that are avoided through seaweed because there are multiple approaches being developed simultaneously. Each approach needs bespoke certification and verification. VERRA is seeking to develop a series of verified methodologies in the coming years. The routes to certifying ecosystem services take years to formalize. 2. There is insufficient communication to harness public support, and inadequate cooperation and coordination to prevent or at least markedly reduce competition for space with existing ocean stakeholders, particularly in emerging seaweed regions. 3. There is a need for more legislation and governance to incentivize sustainable seaweed farming practices and facilitate the approval of new seaweed farming licenses. 4. Globally, there is a need for more and better talent/human resources. In developed seaweed regions, several interviewees noted a shortage of fresh talent entering academia. 5. Farmed biomass for carbon credits might end up being sold into other markets because of higher price points.

5.7. Market outlook

Outlook for blue carbon

According to stakeholders interviewed for this report, the voluntary carbon market is the leading route to valorization. This stems, in part, from the heightened appetite for carbon credits around the world. International demand for carbon offsets is increasing as organizations and nations seek to reduce their greenhouse gas emissions. Although seaweed has not yet been included in internationally recognized blue carbon credit schemes, multiple regions and organizations are working on this and offering ways to pay people to farm or restore seaweed for carbon uptake and sequestration purposes.

For example, China and South Korea have both included seaweed aquaculture as a blue carbon habitat. Additionally, on November 21, 2022 the sea urchin ranching company Urchinomics became the first business to receive a voluntary blue carbon credit for restoring kelp beds (Loew 2022). The credit was awarded by the Japan Blue Economy Association (JBE).

Several other organizations have been developing frameworks to include seaweed in blue carbon markets. For example, in 2021, the Kelp Forest Foundation engaged Carbonomics, a leading developer of carbon-offset projects, to write and present a certification concept to Gold Standard. If approved, the concept note will be turned into a methodology for carbon-crediting kelp ecosystems.

Oceans 2050 and GreenWave have also been calculating blue carbon produced from seaweed farming. The former has submitted a proposal to VERRA to certify their methodology. Stakeholders interviewed for this report suggested that, by 2025, it is highly possible that internationally recognized credit certification schemes for blue carbon seaweed projects will exist, alongside more concrete methodologies for implementing both wild and cultivated seaweed in voluntary blue carbon markets. Table 35 below shows how predictions vary between different methodologies. Research undertaken for this report suggests that kelp forest restoration and seaweed sediments will likely be the quickest to access international credit markets. However, insufficient MRV and slow certification procedures could stall these predictions.

TABLE 35: Challenges facing seaweed as an ecosystem service

Ecosystem Service	Valorization Strategy	Technical challenges (1–10)	Regulatory challenges (1–10)	Social challenges (1–10)	Financial challenges (1–10)	Political challenges (1–10)	Overall challenge ahead	Time to establishment of viable monetization/ valorization model (yr.)
Carbon removal	Deep-ocean sinking and sequestration credits	7	6	8	6	6	7	3–8
	Sediment credits	4	4	4	4	4	4	<2
	Natural carbon export credits	5	4	4	5	4	5	3–8
	Restoration credits	4	2	2	4	4	3	<2
Methane emission reduction	Methane Reduction Supplements	6	6	2	4	2	4	(already deployed)
Bio-remediation	Payment for land-based bioremediation	6	4	2	5	2	4	(already deployed)
	Payment for ocean-based bioremediation	4	4	4	4	4	4	3–8
Wider ecosystem services	Biodiversity enhancement payment	5	4	3	4	4	5	3–8

Note: 1 = the least significant challenges, 10 = the most significant challenges

Time to global commercial scaleup is also noted, assuming that the major challenges are surmountable

Outlook for bioremediation

The demand for bioremediation, particularly nitrogen removal, has been increasing worldwide as governments, NGOs, and individuals seek to minimize eutrophication and harmful algal blooms, which can significantly impact tourism and aquaculture operations. Point-source, land-based seaweed bioremediation operations have proven to be commercially viable for a number of years. Recent market developments from regions such as Australia and New Zealand (for example, Pacific Bio and Aqua Curo) are showcasing the scaleup potential of this application. These organizations are piloting and commercializing the clean-up of wastewater from various industrial settings. Based on interviews undertaken for this report, this application of macroalgae is expected to scaleup in the next 12 months.

Valorizing the bioremediation potential of ocean farming and macroalgae-based IMTA is also gaining greater awareness among regulators, corporations, and the public. Attention is shifting toward developing the service. A nine-fold increase in annual publications in the Web of Science between 2010 and 2020 for the search string "seaweed" and "bioremediation" underscores the heightened interest in the space (Web of Science, accessed Jan. 16, 2023).

Unfortunately, there is currently a lack of internationally recognized payment-for-nutrient-removal schemes and credits that incorporate seaweed. However, stakeholder interviewees predicted that these could develop before the end of 2026. A lack of awareness was highlighted as one of the major barriers. Meanwhile, various organizations are already moving ahead by paying farmers for bioremediation through subsidy schemes. For instance, GreenWave's Kelp Climate Fund supports farmers by providing a subsidy for nitrogen. In return for payments from GreenWave, farmers provide key monitoring data. GreenWave aggregates these data to track acres planted, nitrogen removed, and volumes harvested throughout North America.

Outlook for methane reduction

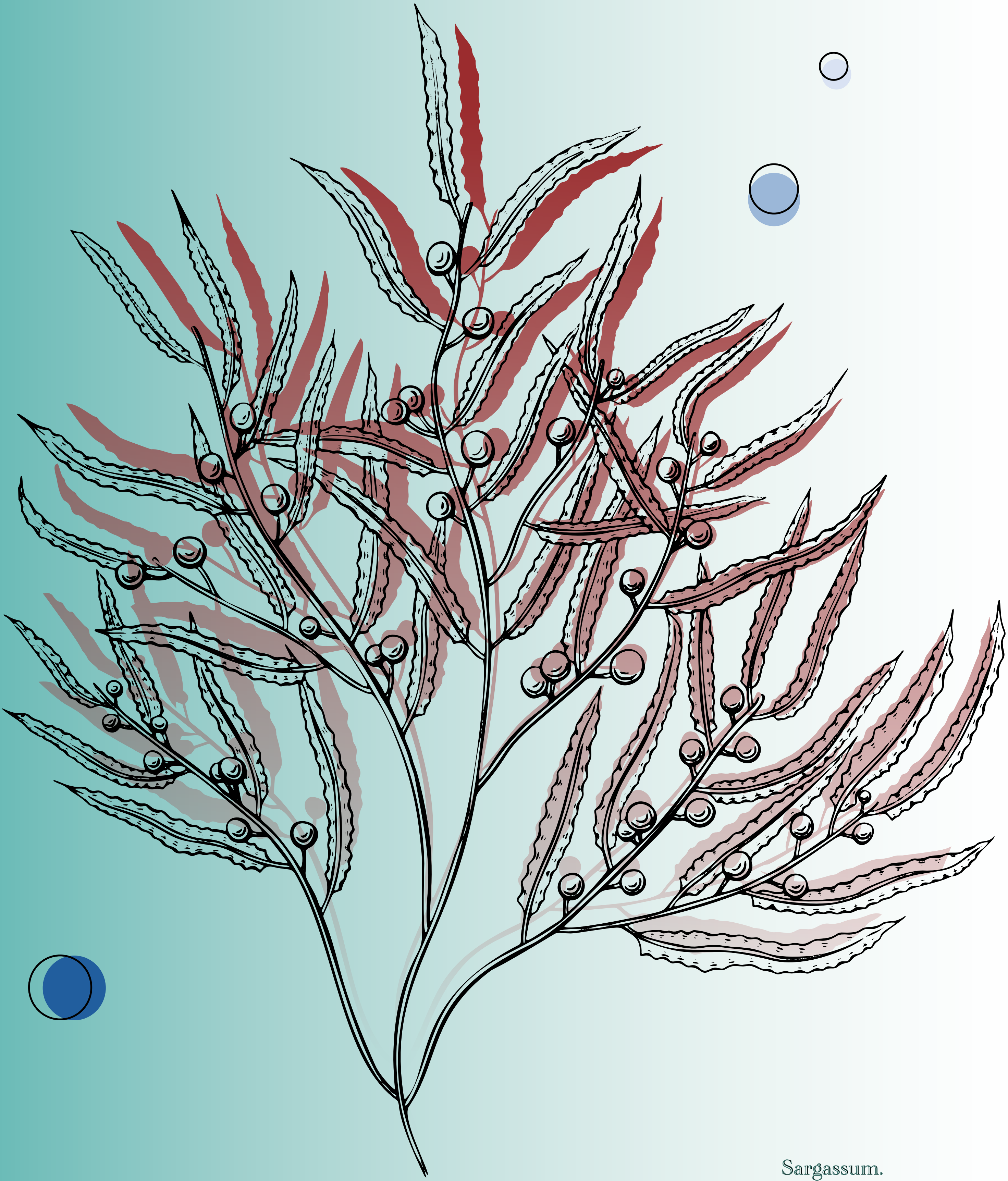
See chapter 4, section 4 for market outlook.

Outlook for biodiversity and wider ecosystem benefits

Several stakeholders interviewed suggested that biodiversity enhancement could become one of the more important ecosystem service attributes of seaweed farming and restoration over the next decade. Given the important role seaweed plays in habitat provisioning, various governments have funded research in this area to further explore its potential. For instance, the Canadian government recently committed $104 million (CAD$142 million) to the British Columbia Salmon Restoration and Innovation Fund (BC SRIF). Cascadia Seaweed received capital from this fund to plant 3.5 hectares of seaweed to study the interaction between kelp farms and fish biodiversity. EnviroStrat in New Zealand has a $5 million seaweed farming pilot under way that includes quantifying the biodiversity impacts of *E. radiata* farming. In addition, wind farm developer Orsted recently partnered with SeaGrown to explore the use of seaweed cultivation in improving ocean biodiversity.

Overall, there is increasingly greater global focus on biodiversity enhancement solutions. Several stakeholders noted the important outcome of the United Nations Biodiversity Conference (COP15) in 2022, in which the Kunming-Montreal Global Biodiversity Framework (GBF) was adopted to address the loss of biodiversity, restore ecosystems, and protect indigenous rights (*COP15 ends with landmark biodiversity agreement* 2022). Based on this interest, the stakeholders interviewed for this report predicted that from 2023-2026, there will be significant investment in this area. Credit schemes will be the likely route for valorization, but more time and effort are required for accurate MRV and accreditation.

Alternative regulating or provisioning ecosystem services, such as coastal protection and enhanced coastal resilience, have a lower profile, and governments or companies surveyed working in these areas are typically at the pilot stage. It may take several years before we see commercial scaleup of these applications. However, interviewees indicated that these services could be more quickly capitalized if they were bundled together into "ecosystem service credits" that present blue carbon, bioremediation, biodiversity, and other ecosystem services in a single package.



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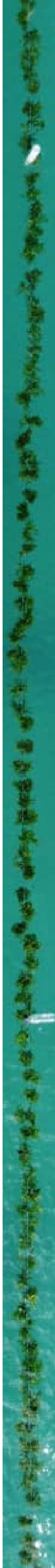
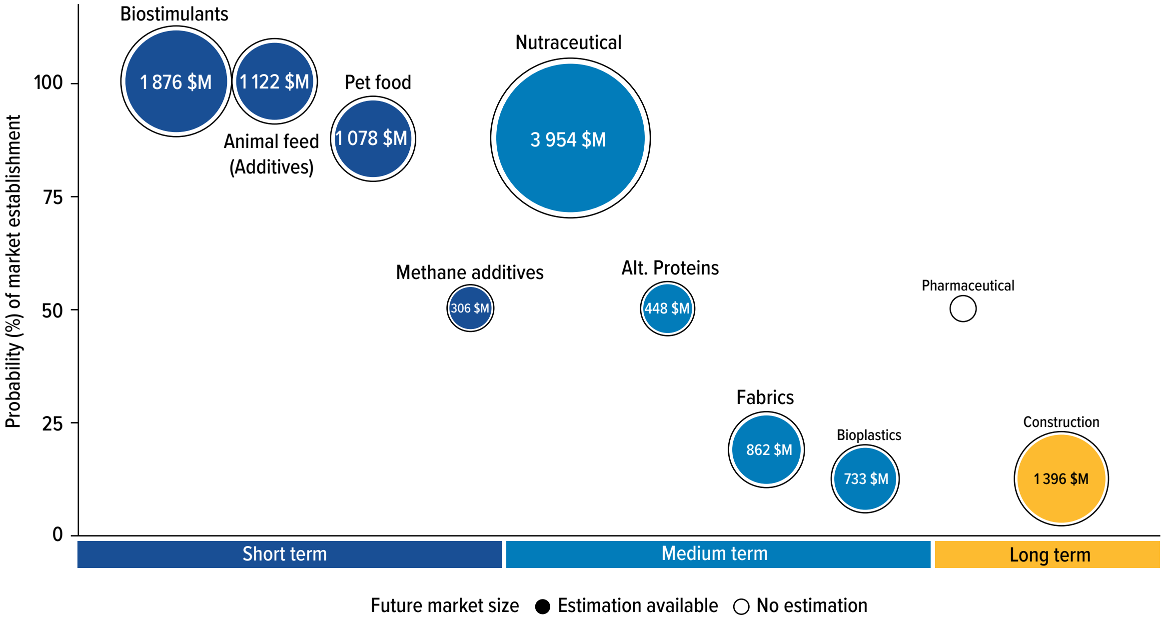


6

CONCLUSION

This chapter ranks the different seaweed applications according to their potential to become significant short-, medium- or long-term markets. It also provides a summary of their respective adoption and growth drivers, challenges, market sizes and market growth rates (see Table A1 in the appendix for a more detailed comparison).

FIGURE 32: Predicted seaweed market size by 2030 ($M) with chance of market establishment indicated by color on a high-level market horizon timeline



6.1. Four short-term markets (before 2025)

Biostimulants, **animal feed additives** and **pet food markets** were identified as the most promising short-term emerging market opportunities for seaweed. In high-growth markets, they already offer a variety of products with competitive value propositions and prices. Compared to other applications, they also present low processing complexity and no severe challenges to further scaling because they can potentially be integrated into existing seaweed supply chains to ensure raw material availability. **Methane-reducing additives** represent a totally novel market. Even though there are presently significant technological and regulatory challenges, there are stronger efforts to overcome those challenges than in many other markets.

Of all the markets assessed in this report, seaweed-based **biostimulants** had the highest market share in 2022 – 30–40 percent. This was worth approximately $1 billion in an overall global biostimulants market valued at $2.5–3.5 billion in 2022. In a high-growth market (10 percent CAGR), seaweed-based biostimulants are expected to maintain their market share and grow to a market value of $1.87 billion by 2030. Even though the global agriculture sector is looking for solutions to support soil health in a changing climate, and fertilizer prices are increasing, seaweed-derived biostimulants could offer a solid value proposition and competitive pricing. Farmed seaweed offers an opportunity to grow the supply significantly because most current feedstock comes from wild-harvested seaweed.

In addition, there is a very high potential for seaweed-based biostimulants to become easy-to-process side-products from the production of other seaweed-derived goods such as pet food and bio-materials. However, biostimulant developers need to provide better evidence of the efficacy of their products and improve end-user education on how to apply them.

Although **pet food** products based on seaweed are already available, no comprehensive data are available on the market's current size. The global pet food market, which is based on bulk feeds and additives, was estimated at $115.5 billion in 2022, with a CAGR of 5.11 percent from 2023 to 2030.

Promisingly for seaweed, the demand for functional pet foods that offer health benefits, and for vegan products with an emphasis on clean labeling, transparency and sustainability, is forecast to increase. Seaweed-based products fit into these categories and could capture a market value of approximately $1.078 billion by 2030. According to interviewees, this is a potentially more attractive market for seaweed producers than animal feed, because the products sell at higher price points, driven by the trend toward "humanizing" domestic pets as full-fledged members of the nuclear family. However, manufacturers first need to conduct more research on the health claims of seaweed-based pet foods, control the levels of minerals such as iodine, markedly reduce contamination from pollutants, and ensure that seaweed-based ingredients are sufficiently palatable.

Seaweed is already used in the animal feed industry as a **feed additive** and feed ingredient, but no data on market size are available. The global feed additive market was valued at $38.86 billion in 2022 and is forecast to grow at 3.9 percent CAGR between now and 2030. As the animal feed industry turns to natural alternatives in preference to synthetic products, seaweed-derived feed additives are expected to gain significant market traction from 2023 to 2028 and reach a potential market size of $1.122 billion by 2030.

At an already competitive price point, the unique functional benefits these seaweed products claim to offer – such as productivity gains, improved feed conversion ratios, and potentially less need for antibiotics – are all highly attractive value propositions for farmers. However, these claims have yet to be confirmed in large-scale trials. A current challenge is the availability of sufficient volumes of seaweed but there are no deal-breaker challenges in this market category.

Methane-reducing additives are a unique case in the new and emerging markets for seaweed, and have gained substantial attention in recent years. Despite being an entirely new segment of the animal feed market, total global methane-reducing additives were valued at $47 million in 2022. As a new market driven by strong demand for net zero policies from corporations and governments, the forecast for a CAGR of 57 percent in the coming years looks feasible.

Seaweed-based products offer an excellent value proposition, with potential productivity gains and route to monetization using carbon credit pathways, and stakeholders predict that commercial scaleup is only a couple of years away. Seaweed-based, methane-reducing additives may reach a market value of approximately $306 million by 2030. However, there are significant challenges because the cultivation of *Asparagopsis* is not widely practiced or well understood, and scaling up production to provide the volumes needed may take time. At the same time, in many geographies the need to gain regulatory approval could hamper market development. Nevertheless, there is clear market demand and the sector is attracting significant investment to overcome these challenges. This momentum may very well help companies to quickly overcome the challenges, as long as a genuine effort is made to avoid unsubstantiated claims that could undermine credibility and trust.

6.2. Four medium-term, emerging market opportunities (2024–2028)

Alternative proteins, nutraceuticals, bioplastics, and **fabrics** are four potential, medium-term markets for seaweed. In recent years, innovative seaweed-based products have been introduced in all these markets, although the number and scale are still limited and mostly restricted to niche applications.

In all four of these submarkets, seaweed-based products will need further refinement in order to gain significant traction in the market. It is expected that this will take a few more years. Those planning to sell seaweed-based products in high-volume markets – such as alternative proteins, bioplastics, and fabrics – must first overcome significant challenges relating to cost, production volumes, and competitive functionality, otherwise these products will likely remain niche offerings.

Alternative proteins derived from seaweed are being sold commercially around the world. The global alternative protein market was valued at $10.2 billion in 2022, and is expected to show a CAGR of 36 percent up to 2030. The primary drivers of this industry include increasing interest in non-animal derived food products, increasing awareness among consumers and product developers of seaweed's multi-functional properties, and potential food supply chain sustainability improvements. The industry could have a market value of $448 million by 2030, but it will have to overcome challenges relating to competition from cheaper biomass alternatives with higher protein concentrations.

Although examples of seaweed-based **nutraceuticals** are already being sold commercially, no comprehensive data are available on their current market size. The size of the overall global nutraceutical market in 2022 was estimated at $450 billion, with a CAGR of 7.5 percent between now and 2030. The increasing prevalence of certain communicable diseases, rising healthcare costs, aging country populations, and greater consumer awareness are all driving the growth of this industry. As a high-value market, nutraceuticals present one of the most promising opportunities for seaweed-based ingredients, with a potential market value of $3.9 billion by 2030. However, a number of challenges make the exact timeline for wider commercial adoption uncertain.

It is reported that many clinical trials are under way, but interviewees submit that there is a need for much more clinical work in order to provide safe products that deliver their claimed health and nutrition benefits. Since clinical trials require time, the commercialization process for nutraceuticals is longer than for many other product segments, which makes this a medium-term market opportunity. There are concerns around the availability and price of seaweed-derived products in this sector, compounded by the complexity and expense of deriving the necessary compounds to create targeted, reliable, and consistent nutraceutical products.

In the **bioplastics** market, there are currently only niche applications, based on biofilms, which are in very early stages of market adoption. The global bioplastics market is valued at $11.5 billion in 2022 and expected to increase by a CAGR of 20 percent between 2022 and 2030, driven by global ambitions to reduce fossil-based consumption and plastic pollution. The future market for seaweed-based bioplastics could be worth $733 million by 2030, but it will have to overcome significant challenges to grow beyond niche applications. A significant section of this market – consumer-packaged goods – could provide a beachhead for this category owing to the biodegradability of seaweed-based bioplastics and the willingness of many consumers to pay a premium for sustainably sourced packaging.

In the short-term, seaweed-based bioplastic products may fulfil niche applications while remaining many times more expensive than competitive bioplastics. Despite high R&D budgets and increasing venture capital investment, the integration into existing plastic supply chains will for now remain complex unless their technical performance can match incumbent products. There is evidence that innovators are working on compatible seaweed-based resins that could be integrated into existing production systems, but this process will likely take 5–10 years of research and development, and its success is not guaranteed. The second major challenge is to meet the production scale required to bring prices down to competitive levels.

There is growing interest in producing seaweed-based textiles, although applications remain in the early research or pilot product stages. Lyocell-based seaweed textiles (with a maximum seaweed content of 10 percent) are commercially available, but the industry remains too small for precise market sizing.

Generally, the rising interest in seaweed-based textiles is part of a greater trend toward biosynthetic textiles. Typically made from crops, and less frequently from forestry residues or agricultural waste, biosynthetic textiles are intended to disrupt fossil-based synthetics. Valued at $17.18 billion in 2022, the global biosynthetic textile market currently accounts for less than 1 percent of the global textile market, yet is expected to grow at an annual rate of 10 percent between 2022 and 2030.

The market's growth mirrors rising concern about the climate impact of the fashion industry, and seaweed's environmental value proposition aligns well with corporate sustainability targets. However, to reach a potential $862 million market size by 2030, seaweed-based product developers will have to significantly improve processing technology. Although it is likely that the market share of Lyocell with added seaweed extracts will increase, for the higher percentage seaweed-based products to reach the market, there needs to be performance improvements, together with increased regulatory and market pressure on corporations to adopt more sustainable fabrics. Seaweed-based fabrics face stiff competition from alternative biomasses but they can potentially be blended with other bio-based feedstocks to create products competitive with conventional options such as cotton.

6.3. Two long-term, emerging-market opportunities (after 2028)

Pharmaceuticals and construction were identified as potential long-term market opportunities for seaweed. In both markets, seaweed-based products are not yet commercially available and will have significant challenges to overcome before they get to market.

Pharmaceuticals

Market projections in the seaweed-derived pharmaceutical space are difficult to make. No approved products are currently on the market, and a single commercialized product could generate significant revenue. The market for marine-derived drugs is currently estimated at $2.56 billion, with an annual growth rate of 5–10 percent up to 2030. The increasing demand for effective and innovative therapies continues to drive long-term growth in the pharmaceutical area and seaweed-derived compounds offer promising functionalities. Since most trials on seaweed-based pharmaceuticals are preclinical, it is expected that these will take at least 5–10 years before becoming government agency-approved pharmaceuticals and will require significant financing to progress.

Construction

Seaweed construction materials show promise, particularly in niche applications such as fiberboard or bioplastic panels in interior design projects. The global green construction materials market was valued at $312.5 billion in 2022 and is expected to maintain a CAGR of 10 percent until 2030. The seaweed construction market could be worth $1.4 billion by 2030, but before this figure can be reached, significant challenges need to be overcome – specifically, around the availability of biomass, the higher costs of seaweed-based materials compared to traditional bio-based materials, and the industry's resistance to change. Nevertheless, in regions where seaweed is abundant, such as the Caribbean with its *Sargassum* blooms, there is significant interest in scaling up seaweed construction operations, driven by buyer demand.

6.4. Additional conclusions

Seaweed supply constraints exist on all new and emerging market applications and are strongest where market value can be derived only from a specific species of seaweed, especially those that are currently available only in small volumes. This bottleneck is compounded by a second constraint – namely, that much of the product development is taking place in the West, where seaweed supply, especially from farmed sources, is particularly poor. In this context, further investment in Asia is likely needed – as is the development of pre-processing capacity and technology in order to stabilize biomass and improve its year-round availability, thereby increasing asset utilization in downstream processing.

A third constraint is that current main markets, including seaweed for human consumption and hydrocolloids, are growing steadily, so any new markets will have to compete for biomass with these established supply chains. This emphasizes the need for significantly increased primary production of seaweed.

The **high price of seaweed-derived compounds** is a fourth constraint on several applications assessed in this report. The more the application competes with commodity or commodity-derived products (for example, plastics or construction materials), the greater is the pricing challenge. For market sectors with very high price challenges, it is entirely possible that seaweed-based products will remain a specialty niche.

The need to develop and adopt new technologies imposes a fifth constraint, and is an important prerequisite for scaling up the production of seaweeds and their derivatives. There is a consensus that the development and application of a multi-product **biorefinery** approach will help create an economically viable process. Biorefineries are capable of efficiently extracting a range of products, but most seaweed biorefinery systems are still at the laboratory or pilot level. More seaweed needs to be produced to ensure that these facilities can reach commercial scale.

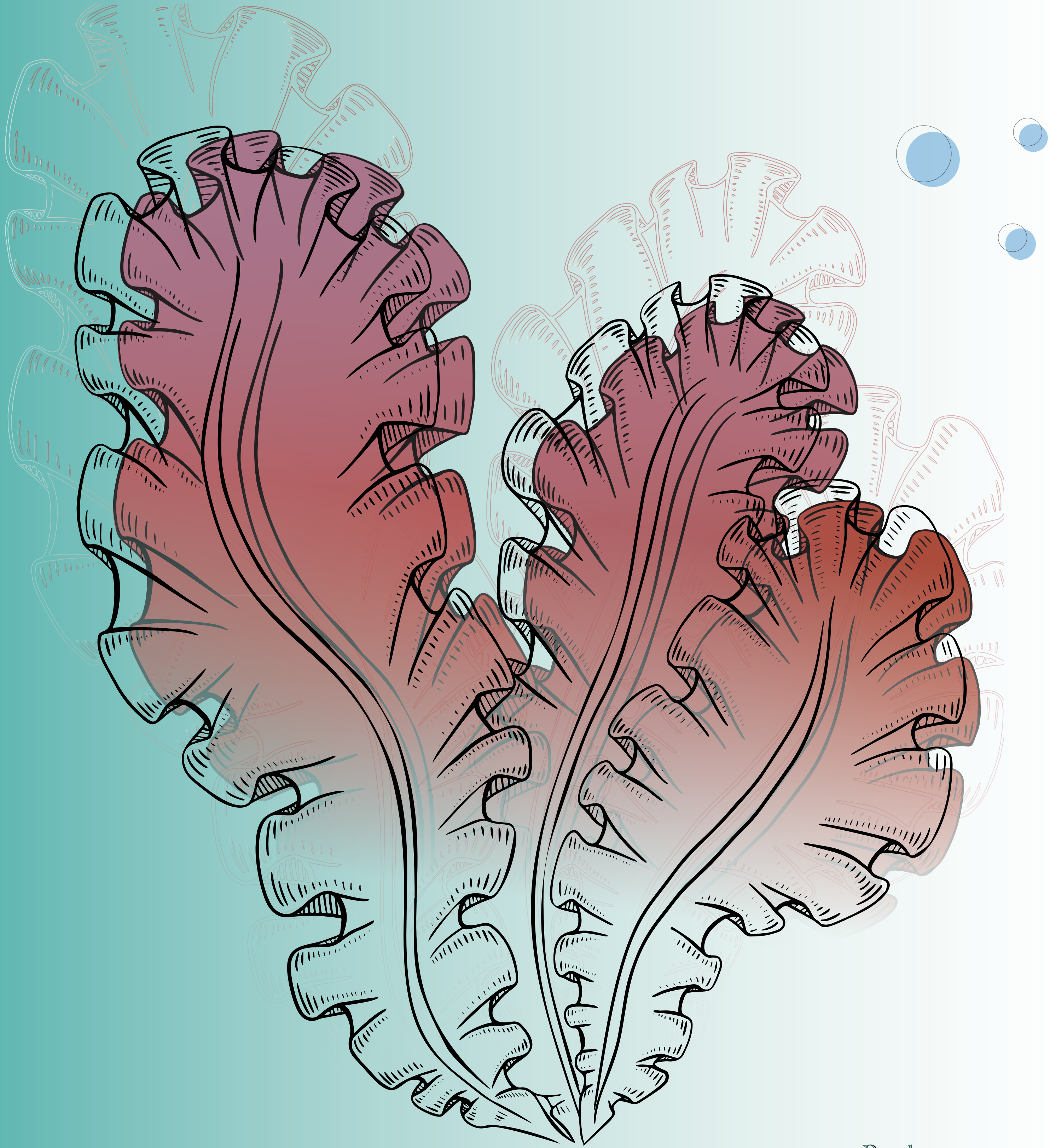
Current and future competition is another constraint. Although the markets in this report have been analyzed individually as if they were neatly compartmentalized, it is important to bear in mind that **competition among the seaweed-based product categories** exists and can impact future market development and value significantly. It is only to be expected that, once a higher-value market for a particular compound or product becomes more accessible, producers will target that new market to maximize their profits, which in turn generates greater competition.

Any **regulatory hurdles** that some of the higher-value markets are presently facing will play an important role and could change a market's trajectory significantly. In addition, it is often unclear under which regulatory category seaweed-derived products fall – and therefore how they should be regulated. As a result, products often miss out on supportive frameworks and subsidies.

Given that the majority of the applications analyzed are pre-commercial, it is clear why **finance** is seen as one of the most substantial challenges. Most applications for seaweed-based products present a high market risk, because of the significant scaling challenges described here, reducing their appeal to investors. Many early business models rely on obtaining **sustainability premiums** which can be both an opportunity and a risk – while seaweed-based product developers hope to justify a green premium, consumers might not be willing to pay those. In addition, there is a clear need for LCAs across all applications to verify sustainability claims and to inform the decision making of investors.

A great deal of attention is currently being directed toward **ecosystem services** generated by farming seaweed – such as blue carbon, bioremediation, and biodiversity – and the associated potential to improve the business case of developing seaweed-based value chains. Seaweed clearly has the potential to provide significant ecosystem services but the monetization of these will require the further development of certification and credit schemes, along with robust monitoring, reporting and verification.

To sum up, the seaweed sector has unquestionable potential for growth beyond its current markets, but it is important to be realistic about the sector's scaleup challenges across various applications. Seaweed alone cannot by itself solve the growing climate, food security, and biodiversity crises. Although the sector is nascent and on the rise in the West, where it is has been met with enthusiasm and optimism, the current signs of decline in Asia's already industrialized seaweed sector points to the need to proceed with caution.



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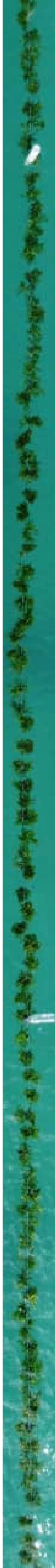

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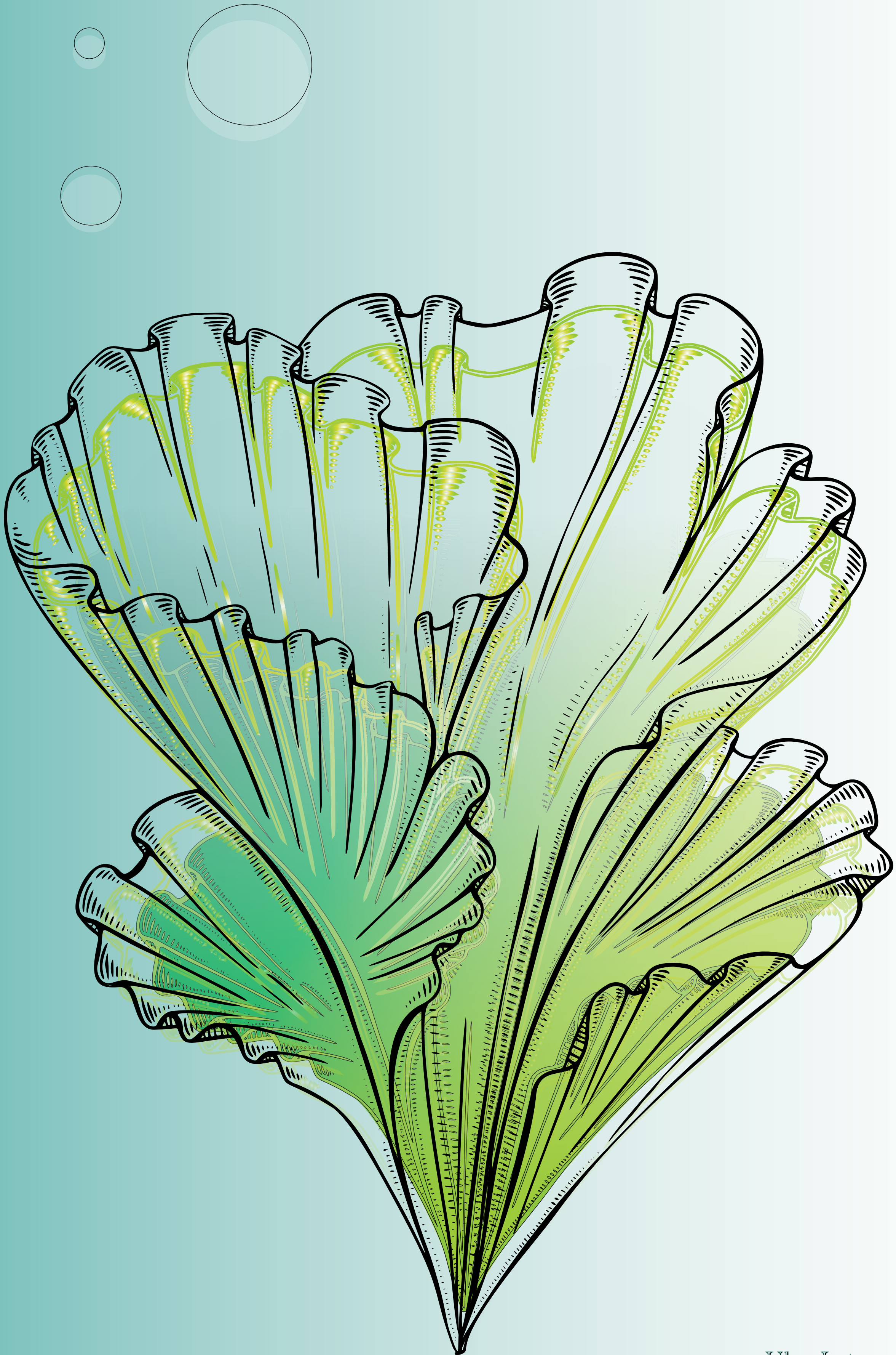

Ulva Latuca.

APPENDIX

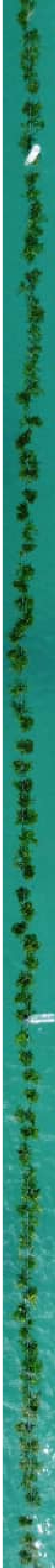

TABLE A1: Breakdown of different markets investigated in the report

Short-term markets (before 2025)				
Application	**Projected seaweed market size (2030)**	**Primary drivers**	**Main challenges**	**Outlook**
Biostimulants	$1.8 billion	1. Growing focus on sustainable farming that supports soil health in a changing climate. 2. A significant increase in fertilizer prices. 3. High potential for integration with the production of other seaweed-derived products and existing supply chains, owing to compatible processing requirements. 4. Farmed seaweed offers an opportunity to grow supply significantly; currently most supply comes from wild harvest.	1. Low reputation of biostimulants because of a lack of clear evidence of their efficacy. 2. Complexity in handling the product requires significant efforts in end-user education.	Seaweed-based biostimulants can expect to see vigorous growth over the next few years, as additional investment goes into product development and R&D for improving efficacy, and as more seaweed processors take advantage of this side product.
Animal feed additives	$1.122 billion	1. Increasing public concerns about meat quality and safety, outbreaks of livestock diseases. 2. Productivity gains and the potential to improve feed conversion ratios are economic incentives for farmers. 3. Unique functional benefits of seaweed-based products that can help reduce the need for animal antibiotics. 4. Costs of seaweed-based products are already competitive with other feed additives.	1. Unavailability of sufficiently large volumes of seaweed. 2. Lengthy customer onboarding and the high cost of demonstrating results through large-scale trials.	Seaweed-derived feed additives are expected to outpace other applications by 2028.There are powerful drivers as customers turn to natural alternatives in preference to synthetic products. Improvements in feed conversion ratios are especially promising.

(Table Continued)

TABLE A1. ***Continued***

Short-term markets (before 2025) *(continued)*					
Pet food	$1.078 billion	1. Increasing demand for vegan products with an emphasis on clean labeling, transparency and sustainability. 2. Increasing preference for functional pet foods with augmented health benefits.	1. Unavailability of sufficiently large volumes of seaweed. 2. Highly consolidated market. 3. Insufficient research to support health claims, excessively high levels of minerals such as iodine, contamination from pollutants, low palatability.	According to interviewees, this is a potentially more attractive market for seaweed producers than for animal feed, particularly in areas where the price of farming seaweed is high. Products are generally more expensive than animal feed, driven by the trend toward the ”humanization” of domestic animals and demand for healthier alternatives.
Methane -reducing additives	$306 million	1. Demand from consumers for more sustainable meat and dairy products, coupled with net-zero policies from corporations. 2. Economic incentives: potential productivity gains and route to monetization using carbon crediting pathways.	1. Competition from synthetics 2. Availability of sufficiently large seaweed volumes. 3. For many companies, there is single species risk, as cultivation of *Asparagopsis* is neither widely practiced nor deeply understood. 4. In many geographies, speed of regulatory approval may be slow, unless more time is spent on broadening awareness.	Stakeholders predict that commercial scaleup is only a couple of years away. There is clear market demand for this product and the sector is attracting significant investment to overcome these challenges. This momentum may allow the challenges to be overcome faster than for other markets, as long as unsubstantiated claims are avoided.

(Table Continued)

TABLE A1. ***Continued***

Medium-term, emerging-market opportunities (2024–2028)				
Nutraceuticals	$3.9 billion	1. Rise in prevalence of several communicable diseases. 2. Rising healthcare cost. 3. Aging populations and increased consumer awareness.	1. Quality and certification of nutrition claims require expensive and lengthy clinical trials. 2. Quality and consistency of seaweed supply, combined with the complexity and expense of deriving the necessary compounds to create targeted and measurable nutraceutical products.	One of the most promising high-value opportunities for seaweed-based ingredients. However, major challenges make the exact timeline for wide commercial adoption unclear. It is reported that many clinical trials are under way, but interviewees report there is a need for much more clinical work to provide safe products that deliver the claimed health and nutrition benefits. Since clinical trials require at least 2 years, often longer, this could reduce the speed of commercialization.
Alternative proteins	$448 million	1. Increasing interest in non-animal-derived protein products. 2. Increasing awareness among consumers and product developers of the multi-functional properties of seaweed, its balanced profile of essential amino acids, and potential food supply chain sustainability improvements.	1. Cost of production of high-protein concentrates. 2. Competition from other, cheaper biomass that has higher protein concentrations. 3. Technical challenges with protein extraction. 4. Availability of sufficiently large seaweed volumes with consistent protein contents.	Development of seaweed proteins as white-labeled ingredients to compete with other alternative proteins, such as pea or soy, is being explored by a number of companies. It was also reported that protein extracts from seaweed would only be part of a wider biorefinery approach, and may gain competitive advantage only if some other function – such as binding or gelling – can be provided in a single-source ingredient.

(Table Continued)

TABLE A1. ***Continued***

Medium-term, emerging-market opportunities (2024–2028) *(continued)*				
Fabrics	$862 million	1. Increased regulatory and market pressure on fashion industry firms to adopt more sustainable fabrics in their products. 2. Corporate sustainability targets align with seaweed sustainability value proposition.	1. Cost of production 2. Requires more sophisticated processing methods for higher seaweed inclusion rates, while improving performance. 3. Competition from alternative sustainable materials with lower price points and superior properties. 4. Availability of sufficiently large seaweed volume at consistent quality and low price.	Although it is likely that the market share of Lyocell with seaweed extract will increase, for higher-percentage seaweed-based fabrics to reach market, performance improvements will be necessary. One advantage is that seaweed-based fabrics can more easily be blended with other bio-based feedstocks to create products competitive with conventional products such as cotton.
Bioplastics	$733 million	1. Globally, businesses are aiming to "Go Green" and achieve their carbon-neutrality goals. 2. High R&D budgets and substantial VC investments.	1. Cost of production and process parameter requirements. 2. Integration into existing plastic supply chains is complex, unless technical performance can match incumbent products. 3. Competition from alternative bio-based plastics with lower price points and better properties. 4. Availability of sufficient seaweed volumes at consistent quality and low price.	There is evidence that innovators are working on compatible seaweed-based resins that could be integrated into existing production systems, but this process will take 5-10 years of R&D, and success is not guaranteed. In the short term, seaweed-based products may fulfil niche applications while they remain multiple times more expensive than competitive bioplastics.

(Table Continued)

TABLE A1. ***Continued***

Long-term, emerging-market opportunities (beyond 2028)				
Pharmaceuticals	N/A (due to lack of available data)	1. Increasing demand for effective and innovative therapies.	1. Several of the larger seaweed-based bioactives currently under investigation suffer from batch-to-batch variability and the associated challenges of preparing high pharma-grade (>98 percent pure) material. 2. Long timelines to perform clinical trials and overcome regulatory hurdles. 3. Capital requirements of R&D and clinical trials. 4. Some competition from microalgae-derived compounds – for example, fucoxanthin.	Since most work on seaweed-based pharmaceuticals is preclinical, it is expected that these will be at least 5–10 years away from becoming approved pharmaceuticals. Requires significant financing to progress.
Construction	$1.4 billion	1. Demand for green buildings that reduce the use of finite resources. 2. Potential for carbon sequestration in the built environment. 3. Economic incentive from the tourism industry to deal with invasive algae blooms.	1. Cost of production and availability of supply. 2. Resistance to change from the industry. 3. Inherent properties of seaweed, such as its tendency to absorb water in high humidity environments.	Seaweed construction materials show promise in niche applications where premium prices can be charged. Recent changes to bio-based construction regulations have been favorable, but this is considered a longer-term market because companies in developing seaweed markets, such as Europe, often face limitations in terms of biomass availability.

TABLE A2: Sources to Table 25: Market value of medically relevant seaweed-derived components of ranging purity

Company	Compound	Price €/kg
IFF (Norway)	Sodium Alginate (GMP)	114,000
research, food and pharma grade	Sterile Ultrapure Alginates PRONOVA (research grade)	456,000
	Sterile Ultrapure Alginates PRONOVA (GMP)	924,000
	Peptide-coupled Alginates NOVATACH (research grade)	2,400,000
ELICITYL (France)	Alginate polysaccharides (from *A. nodosum*)	35,000–200,000
laboratory reagents for R&D only, not human or animal use.	Alginate polysaccharides (from *Chorda filum*)	59,000–400,000
	Alginate polysaccharides (from *Durvillaea antarctica*)	59,000–400,000
	Alginate polysaccharides (from *Fucus vesiculosus*)	35,000–200,000
	Alginate polysaccharides (from *Laminaria japonica*)	350,000–500,000
	Fucoidan polysaccharide (from *Chorda filum*)	590,000–1,650,000
	Fucoidan polysaccharide (from *F. vesiculosus*)	2,755,000–3,500,000
	Fucoidan polysaccharide (from *Durvillea antarctica*)	590,000–850,000
	Fucoidan polysaccharide (from *A. nodosum*)	590,000–850,000
	Fucoidan polysaccharide (Kit. 4 items each in 100 mg pack size)	6,050,000
	Fucoidan oligosaccharides (Cut-off < 10kDa from Chorda filum)	5,900,000–12,000,000
	Galactofucan polysaccharide (from *Undaria pinnatifida*)	1,605,000–2,400,000
	Ulvan polysaccharides from *Enteromorpha* sp. (research / native grade)	160,500–240,000
	Ulvan polysaccharides from *Enteromorpha* sp. (research / fine grade)	2,575,000–3,850,000
	Ulvan polysaccharides from *Ulva* sp. (research / native grade)	160,500–1,200,000
	Ulvan polysaccharides from *Ulva* sp. (research / fine grade)	1,113,000–3,850,000
Marinova (Australia/ Tasmania)	Fucoidan polysaccharide (*Undaria pinnatifida* and *Fucus vesiculosus*)	approx. 320,000–900,000
Merck (Germany) / Sigma-Aldrich / Supelco	Fucoxanthin (analytical standard, ≥ 95%)	49,400,000
	Fucoidan (from *Macrocystis* pyrifera, ≥85%)	390,000
	Fucoidan (from *Undaria pinnatifida*, ≥ 95%)	518,000
	Fucoidan (from *Fucus vesiculosus*)	760,000
	Fucoidan (from *Fucus vesiculosus*, ≥ 95%)	518,000
	Calcium alginate	3,640
	Alginic acid (*Macrocystis* pyrifera (kelp), mixed polymer of mannuronic and guluronic acid)	304
	Sodium Alginate (bioreagent)	426
	Carrageenan	708
	L-(−)-Fucose	31,500

(Table Continued)

TABLE A2. ***Continued***

Company	Compound	Price €/kg
	ι-Carrageenan (commercial grade, type II, mainly iota)	664
	κ-Carrageenan	1,410
Supelco	Carrageenan (blended from various seaweeds, for gel preparation)	708
	Sodium Alginate	126
	Sodium Alginate powder	412
	Sodium Alginate (Pharmaceutical Secondary Standard; Certified Reference Material)	185,000
	Fucoxanthinol (analytical standard)	795,000,000
Yeastech (US)	Agar, pharmaceutical grade (USP) agar	300
	Agarose (Molecular biology grade)	1,700–4,000
Grainger (US)	Agar agar (research grade)	200–500
	Agarose (analytical reagent)	2,000–4,000
	Sodium Alginate (NF/research grade)	150–400
	Carrageenan (iota- and kappa-type, research grade)	250–350
PanReac AppliChem and the ITW Reagents Division (Spain/ Germany/Italy)	Agar (USP-NF) pure, pharma grade	975
	Agar powdered pure, food grade	144
	Agar, technical (Ingredient) for microbiology	260
	Agarose Basic	655
	Sodium Alginate (GMP)	171
Special Ingredients Ltd (UK)	Agar-agar powder, food grade E406 (produced in Europe)	38
	Carrageenan Kappa, food grade E407 (produced in Europe)	40
	Carrageenan Iota, food grade E407 (produced in Europe)	40
	Sodium Alginate, food grade E401 (produced in Europe)	45
Selleck Chemicals	Fucoidan (Purity: 99.90%)	940,000
Others/diverse (China)	Agar-agar powder, food grade E406 (red algae, produced in China)	50
Hangzhou Source Herb Bio-Tech Co., Ltd. (China)	Supply Kelp Extract Fucoidan 10%–95%	48–480
Beijing Mesochem Technology Co., Ltd.	99% Assay Raw Material Fucoidan Powder CAS 9072-19-9 Pharmaceutical Powder Fucoidan	10–100
Xi'an Tonking Biotech Co., Ltd.	High-Quality Natural Seaweed Extract Powder Fucoidan 85%	20–220
Shandong Meihuayuan Industry and Trade Co., Ltd.	Sodium Alginate CAS 9005-38-3	3.5–10

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