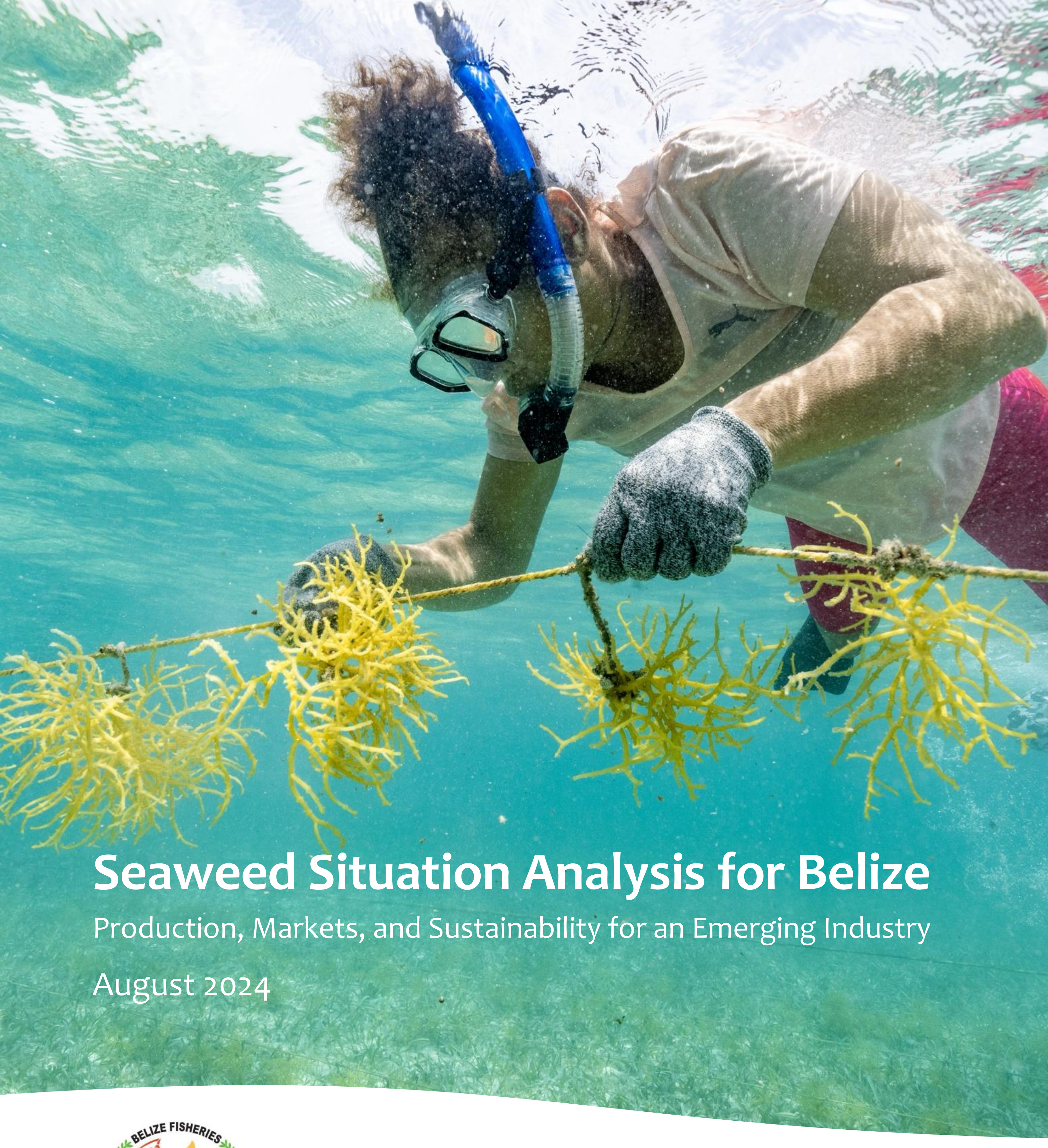

Seaweed Situation Analysis for Belize

Production, Markets, and Sustainability for an Emerging Industry

August 2024

Belize Fisheries Department

The Nature Conservancy

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Photo and Illustration Credits

Cover: A snorkeler tends to a sustainable seaweed farm in Belize, which provides economic opportunity and creates a habitat for marine species. Photo credit: Jennifer Adler.

Section cover: A farmer stands among the cultivation lines of a seaweed farm. Photo credit: Seleem Chan.

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List of Abbreviations

ASC	Aquaculture Stewardship Council
BAFS	Philippine Bureau of Agriculture and Fisheries Standards
BAHA	Belize Agricultural Health Authority
BELTRAIDE	Belize Trade & Investment Development Service
BMP	Best Management Practices
BZD	Belize dollar
CAGR	compound annual growth rate
FAO	Food and Agriculture Organization of the United Nations
FSMS	food safety management system
GAqP	Good Aquaculture Practices
HACCP	Hazard Analysis Critical Control Point
ISO	International Organization for Standardization
MBECA	Ministry of the Blue Economy and Civil Aviation
MPA	marine protected area
MSC	Marine Stewardship Council
MSP	marine spatial plan
NGO	nongovernmental organization
PHA	polyhydroxyalkanoate
PLA	polylactic acid
SCP	sustainable consumption and production
SDG	Sustainable Development Goal
SWOT	strengths, weaknesses, opportunities, and threats
TNC	The Nature Conservancy
UN	United Nations
U.S.	United States
USD	U.S. dollar

Introduction

Belize is a relatively small country situated on the northeast Caribbean coast of Central America, with a population of just above 400,000. Approximately 30% of the population lives along the coast, with the main population centers in urban towns such as Corozal, Dangriga, Punta Gorda, and Belize City (SIB [Statistical Institute of Belize] 2013). Despite its size, the country is culturally, ethnically, and linguistically diverse.

The terrain is mountainous in the central region and low and flat along the coastal region. The country is relatively small, with a mainland coastline of approximately 274 km. It is bordered by Mexico to the north and Guatemala to the west and south, with the Caribbean Sea to the east. Belize has over 400 islands, islets, and cays along its coast. The capital of Belize is Belmopan, located 80 km inland from the coast. The country has the second-largest barrier reef in the world — the Belize Barrier Reef — and the longest in the Northern and Western Hemispheres. The inner reef is comprised of many islets (cays) and three major atolls — Turneffe Atoll, Glover's Reef Atoll, and Lighthouse Reef Atoll. The area receives nutrients from the Eastern Caribbean by way of the Caribbean Current, making it ideal for seaweed cultivation.

The climate in Belize is characterized by two seasons — rainy and dry — and is considered extratropical. The rainy season overlaps with the hurricane season from May to November each year. The dry season is from February to May, with peak dryness observed around April. The temperatures over the year vary from 21 °C to 32 °C, with an average annual temperature of 26.7 °C. These conditions allow for year-round production of agricultural crops such as papaya, oranges, bananas, beans, and potatoes and, more recently, mariculture crops such as

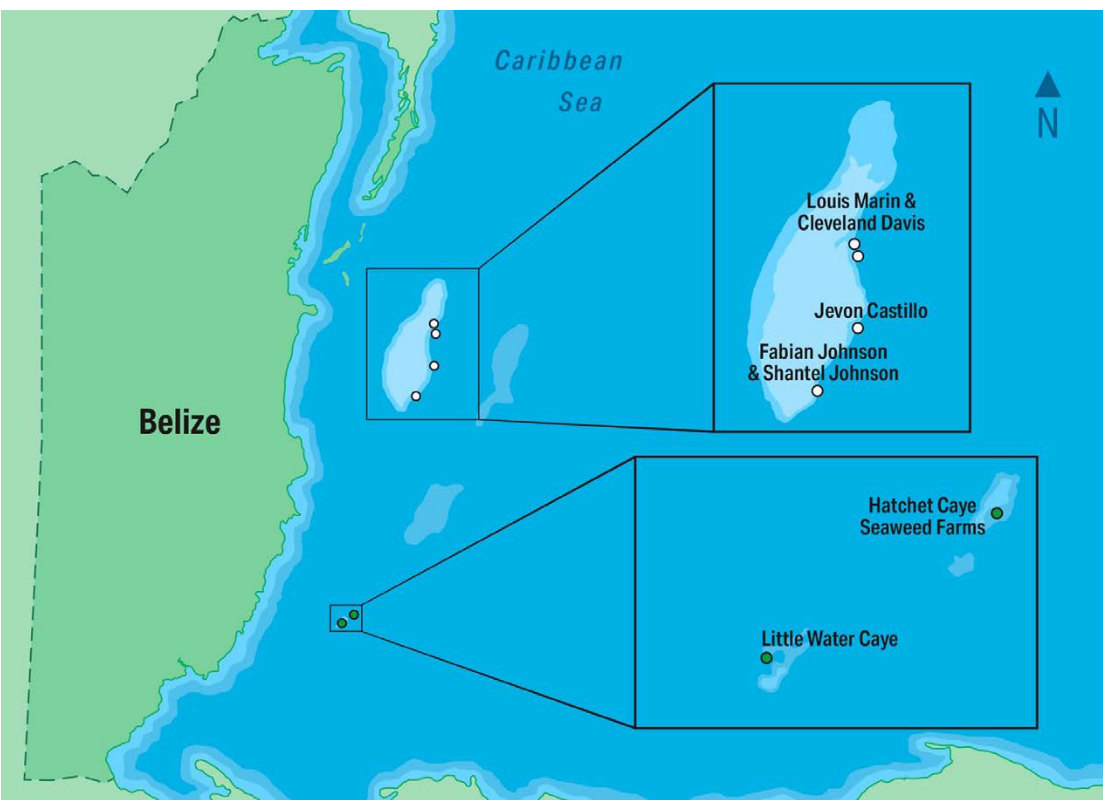

Figure 1. Farmers in Belize include, from north to south, (1) Louis Marin & Cleveland Davis, (2) Jevon Castillo, (3) Fabian & Shantel Johnson, (4) Hatchet Caye Seaweed Farms, and (5) Little Water Caye. Image credit: Jim Kopp.

red seaweeds — specifically, species in the *Gracilaria* and *Eucheuma* genera.

In 2022, all goods and services produced in Belize were estimated to be valued at BZD 1.336 billion (SIB 2023). The economy is primarily dependent on the tourism industry, followed by exports of sugar, bananas, citrus, marine products, and crude oil (World Bank, n.d.). Marine products include both fisheries (lobster, conch, and finfish) and aquaculture or mariculture products such as shrimp and fish (tilapia and cobia). A total of 2500 fishers in Belize benefit from fishing directly, and approximately 15,000 individuals indirectly benefit from the industry (Belize Fisheries Department 2019). The main fishing cooperatives include the National Fishermen Producers Cooperative Society, Northern Fishermen Cooperative Society, Rio Grande Fishermen Cooperative Society, and Placencia Producers Cooperative Society. Seafood production by these cooperatives has historically generated more than USD 10 million annually.

Although the current conditions are suitable for these types of economic activities, Belize is vulnerable to the effects of climate change. The country is at risk of not only sea level rise but also an increased frequency and intensity of storms and hurricanes; examples are Hurricanes Irma and Maria in 2017, both Category 5 hurricanes that devastated the Eastern Caribbean islands. Rising temperatures also threaten to negatively impact agricultural productivity, fisheries, and other economic sectors. These threats require the country to develop alternative industries that will suffer less harsh negative consequences; seaweed cultivation is one of the alternatives at the forefront.

Coastal communities in Belize are well accustomed to a variety of seafood, including seaweed. The harvesting of edible seaweeds in Belize has been ongoing for over 40 years. Seaweed smoothies, shakes, and porridge recipes have been passed down from generation to generation, and seaweed is thought to possess various positive health properties. Today, traditional fishers harvest wild seaweed in areas like Turneffe Atoll Marine Reserve and Glovers Reed Atoll to supply the local demand for seaweed-based beverages.

As recent as the 1990s, individuals from the Placencia Producers Cooperative Society were also harvesting wild seaweed and exporting hundreds of kilograms of dried *Eucheuma* to the United States for use in the food industry. However, over the years, the wild stocks decreased to very low levels and no longer supported export activities. Fishers who traditionally harvested the seaweed realized this and, with the help of local partners and nongovernmental organizations (NGOs), sought out aquaculture as an alternative livelihood and a solution that would allow them to continue selling seaweed without fully depleting the wild stocks. Seaweed farming in Belize has grown slowly for more than a decade, mainly led by small-scale producers such as the Placencia Producers Cooperative (Figure 1).

Seaweed cultivation is known to reduce localized ocean acidification, minimize the potential for eutrophication, and provide habitat for juvenile aquatic organisms (TNC [The Nature Conservancy] 2021). Also, it can supplement or reduce the need for wild-harvesting seaweed. Seaweed cultivation requires no fresh water other than for basic processing for the local market. Thus, seaweed cultivation may be an alternative economic activity attractive to much of the 40% of the country's population living along the coast, particularly in the face of a changing climate that is affecting local fisheries' stocks.

PART 1

Seaweed Production and Markets

History of the Belize Seaweed Industry

There have been many attempts at developing the seaweed industry in Belize for more than a decade due to both the local market demand and the international, multibillion-dollar market that exists for agar and carrageenan derived from species like *Gracilaria spp.* and *Eucheuma spp.* produced in Belize. Funding for the Dangriga Development Initiative in 2002 resulted in the development of test plots off the shore of Twin Cayes in South Water Caye Marine Reserve. The World Wildlife Fund and the Belize Fishermen Cooperative Association sponsored and hosted a seaweed cultivation training workshop in 2005, which covered the cultivation methods for both *Eucheumatopsis isiformis* (syn. *Eucheuma isiforme*) and *Gracilaria spp.*; the training was facilitated by the late Allan Smith of St. Lucia. Funding for farm development and expansion was provided to the cooperative through the Community Management of Protected Areas for Conservation Programme in 2010 and through the Global Environment Facility – Small Grants Programme in 2013.

TNC–Belize also provided financial support to the cooperative in 2014 to improve the management capacity. With the balance of its funding from the 2013 grant, the cooperative developed a seaweed cultivation training manual in 2016. To expand the scale of the training, TNC financed and codeveloped a full seaweed cultivation training program in 2016 in collaboration with the Placencia Producers Cooperative and Coral Caye. The training program consists of a manual, video, curriculum, and both theoretical and practical sessions. TNC's support of the project was and continues to be based on the three-tiered benefits that the farms provide: social, economic, and ecological.

The Belize seaweed industry is in its infancy; production, governance, institutions, and markets are still being developed. The local market purchased approximately 2000 lb (907 kg) of dried seaweed product (10,000 kg wet weight) on average over the last 5 years. Almost all production in the country is a part of the economy of urban and coastal populations, including the two main pilot production areas of Placencia and Turneffe Atoll. Seaweed is sold in the local market, which includes householders, small and midsize retailers, restaurants, and hotels. A small but unknown quantity is also believed to be shipped overseas to the diaspora market in the United States.

This section provides insight into both the global and local Belize seaweed markets and the options for buyers seeking sustainable supply chains for their seaweed products. This section also provides an overview of the issues that should be considered in sustainable seaweed cultivation so that buyers can determine whether the sourced seaweed is sustainable.

Global Seaweed Production Context

Seaweeds are macrophytic algae that lack true roots, stems, and leaves. They are classified as

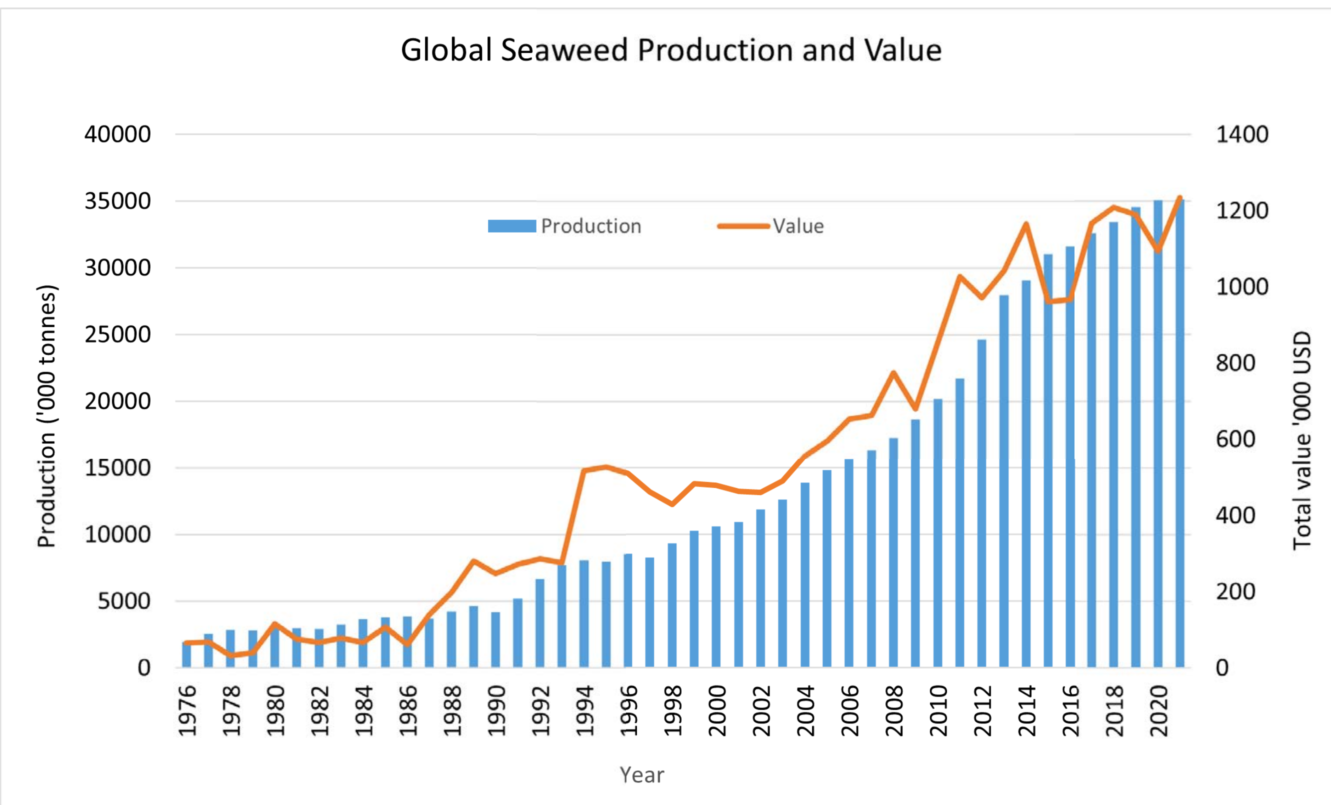

Figure 2. Global seaweed production and value, 1976–2021. Source: Food and Agriculture Organization of the United Nations (FAO 2023).

green algae (Chlorophyta), brown algae (Phaeophyta), and red algae (Rhodophyta). In 2021, global seaweed production, both wild and cultured, was 34.6 million tonnes and valued at USD 15.5 billion (Cai *et al.*. 2021). This production represented a 13% increase over the previous 5 years, continuing an exponential trajectory of between 1.0% and 2.5%, and has increased annually since the 1970s (Figure 2). The trend in the global export of seaweed and seaweed products has followed a similar upward path since the 1970s and was valued at USD 1.2 billion in 2021. World seaweed production continues to be dominated by Asia, whose top five producers are China (57%), Indonesia (28%), the Republic of Korea, the Philippines, and the Democratic People's Republic of Korea (Cai *et al.* 2021). These countries account for over 97% of global production (Table 1). By comparison, the top producers in the Americas, Europe, Africa, and Oceania together account for less than 2% of global production.

The increases in global seaweed production and value reflect the growing worldwide demand for seaweed due to its numerous food and nonfood uses. Consumers, especially in Asia, have become more affluent and have demanded more of what most consider a very healthy and nutritious food source rich in omega-3 and omega-6 fatty acids, vitamins (A, C, E, and B12), and other essential nutrients (Cai *et al.* 2021). Countries are looking to seaweed in the contexts of food and livelihood security for growing populations, restorative aquaculture, and climate change mitigation for sequestering carbon (Ferdouse *et al*. 2018). Also, more industries are demanding the bioactive compounds found in seaweed, such as carrageenan, agar, alkaloids, fatty acids, and polysaccharides, which have uses in the food, agriculture, chemical, medical, pharmaceutical, and construction industries (Zhang *et al.* 2022).

Table 1. Global algae (including seaweeds and microalgae) production by region and selected countries, 2019.

Region/country	**Total seaweed production** (1000s of tonnes)	**Percentage of global production** (%)
Asia	34,882	97.38
China	20,351	56.82
Indonesia	9963	27.81
Republic of Korea	1821	5.09
The Philippines	1500	4.19
Democratic People's Republic of Korea	603	1.68
Americas	488	1.36
Chile	428	1.19
Europe	287	0.80
Norway	163	0.46
Africa	145	0.41
Tanzania	106	0.30
Oceania	17	0.05
Solomon Islands	6	0.02

Note. The total and percentage for a given region do not equal the sum of totals for the region's countries because the countries with the lowest totals were omitted from this table. For a complete list, see the source: FAO (2021).

Global Production and Markets for Red Seaweeds

Global production for red seaweeds

Red seaweeds are the largest group of marine macroalgae, consisting of between 4000 and 6000 species, and can be found attached to rocks or other hard substrata in coastal areas (Kilinc *et al.* 2013). The species diversity is higher in tropical and subtropical waters, such as the Caribbean, Indonesia, the Philippines, China, and other countries with similar climates (Khan and Satam 2003). These seaweeds comprise the primary seaweed group harvested and cultivated in Belize.

Red seaweeds are among the seven most important cultivated aquatic plant species worldwide and include *Eucheuma spp*., *Kappaphycus alvarezii*, *Gracilaria spp*., and *Pyropia spp.* (Cai *et al.* 2021). Seaweeds are grown primarily for use as a carrageenan gelling agent and for agar. They are also grown for human consumption because seaweeds are rich in lipids, polysaccharides, minerals, vitamins, and enzymes, and they have higher concentrations of vitamins B12, B1, pantothenic acid, and folic and folinic acids (Kilinc *et al.* 2013).

In 2019, global red seaweed production was 18.3 million tonnes, accounting for 52.6% of world seaweed cultivation (Cai *et al.* 2021). The price of red seaweed products is known to fluctuate and depends on market factors such as the product origin, season, type of processing, and intended use (Ferdouse *et al*. 2018). Dried *Eucheuma* and *Kappaphycus* prices have been reported as low as 0.2 USD/kg and 0.4 USD/kg, respectively, in Zanzibar (Brugere *et al*. 2020), while the red seaweeds *Porphyra spp*., consumed as a delicacy in Southeast Asia, may have prices of up to 1.2 USD/kg wet weight (McHugh 2003). *Kappaphycus spp.* often have a higher price than that of *Gracilaria spp.* and *Eucheuma spp*.

In the Americas, red seaweeds' total production in 2019 was 22,856 tonnes, and Chile accounted for 94% of the volume from the Americas (Cai *et al*. 2021).

Figure 3. Farmers spread seaweed on a drying rack. Photo credit: TNC.

Current carrageenan and agar markets for red seaweed

The primary products from red seaweed are carrageenan and agar. The carrageenan produced is predominantly the kappa version and is of commercial importance in the food, medical, and cosmetic industries (Vairappan 2021). Agar from seaweed is commonly used in food, where it is prized as a vegan alternative to gelatin.

The global carrageenan market size was valued at USD 871.66 million in 2022 and is expected to expand at a compound annual growth rate (CAGR) of 5.4% from now until 2030 (Grand View Research 2023).

The market demand at a global level is driven by the attractive properties of carrageenan for use in the food industry, mainly as a thickening or gel agent. The primary factor contributing to the wide use of carrageenan in the food industry is its capability to bind with water and enhance the properties of food ingredients. The food and beverage industry used 70% of the global market in 2022, with increasing interest partly from consumer demand for plant-based ingredients (Choudhury 2023). Also, 68.3% of the global carrageenan market uses the iota-form and kappa-form, which are found in high concentrations in the species chosen by Belize farmers.

Moreover, kappa-carrageenan benefits from its suitability for gel-pressed production methods, which are substantially cheaper than alcohol precipitation (Choudhury 2023).

In the United States, carrageenan is used in the food industry and in the personal care market for sunscreen and water-based cosmetics (Figure 4). Europe has approved both refined and semi-refined products for food additive uses.

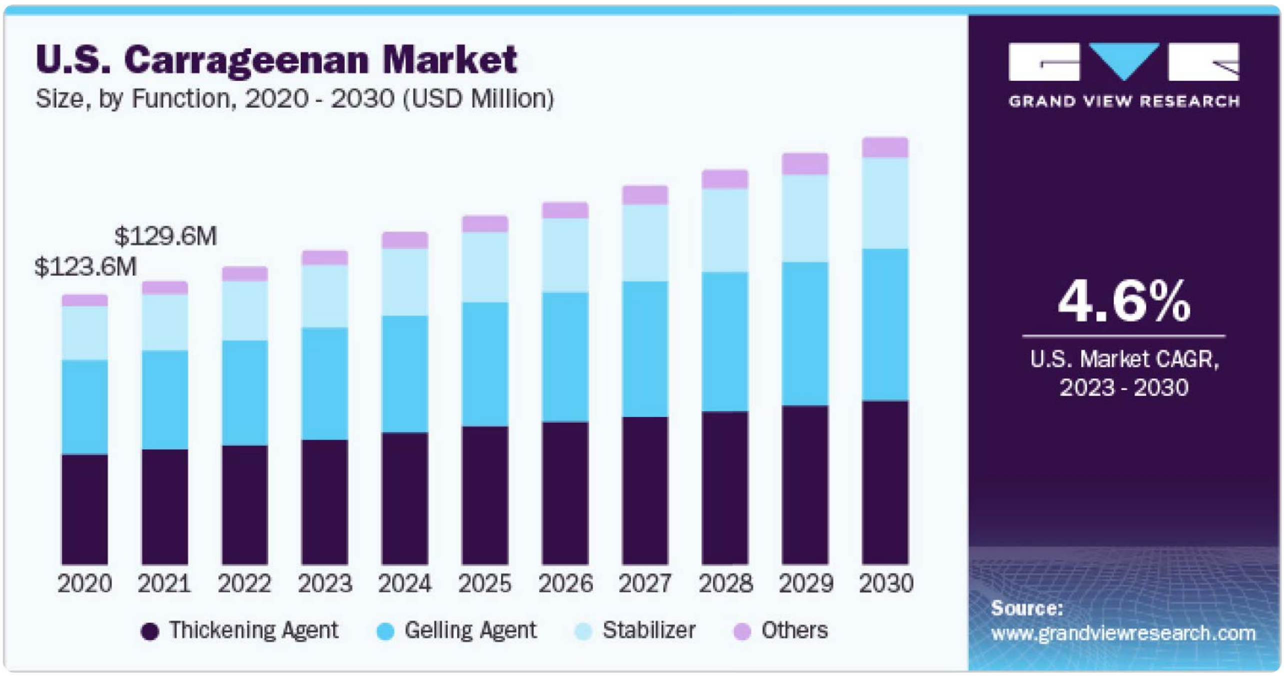

Figure 4. Predicted values of the U.S. carrageenan market and applications. Source: Grand View Research (2023).

The U.S. market is predicted to continue a steady increase in demand for carrageenan for the rest of this decade, and the iota and kappa versions will be suitable for thickening and gelling applications. In this market, the kappa-form is the most in demand for a wider range of applications, whereas the iota-form is used mainly in ready-to-eat meals (Mordor Intelligence n.d.-a). The major players in the country market are Ingredion, Ingredients Solutions, W Hydrocolloids, DuPont, FMC, and Cargill.

Agar is derived from the polysaccharide agarose, which forms the supporting structure in the cell walls of agarophytes of the Rhodophyta phylum (red seaweed), including *Gracilaria crassissima* grown in Belize.

The global agar market was valued at USD 303.49 million in 2022 and is expected to expand at a CAGR of 4.56%, reaching USD 396.64 million by 2028 (Choudhury 2023).

Drivers in the food and beverage market include preferences for halal or kosher food products and increased use of agar in the bakery industry due to its resistance to high temperatures and its superior gelling characteristics in dairy products. Also, agar is increasingly used as a natural ingredient by the food, pharmaceutical, and cosmetics industries (Coherent Market Insights 2023; see Figure 5 for the global agar market share by application).

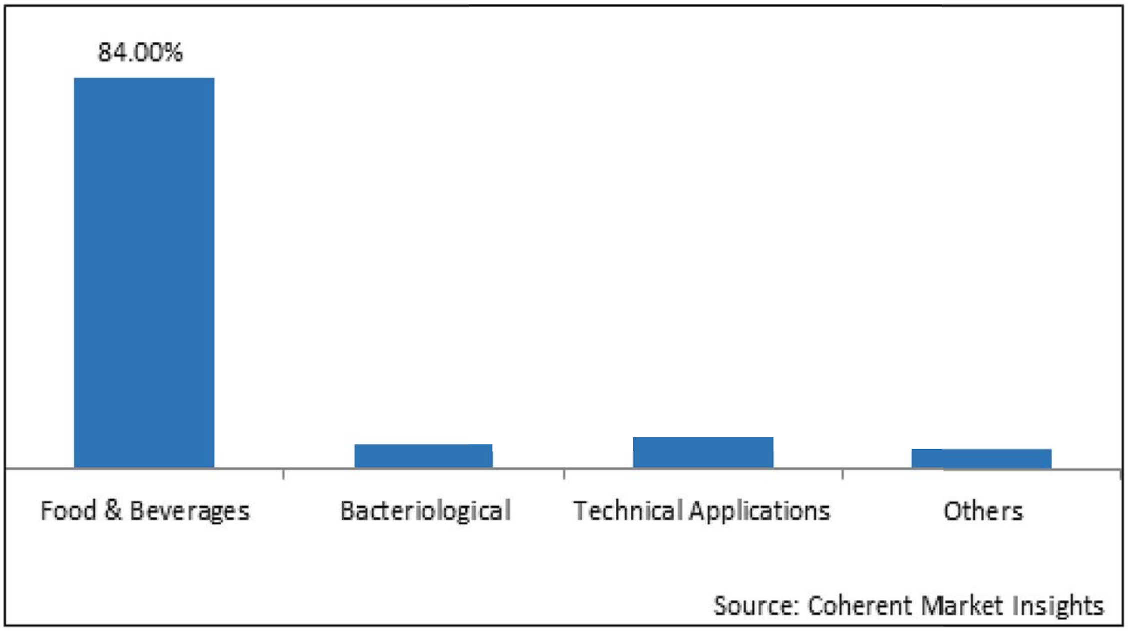

Figure 5. Global agar market value share (%), by application, 2021. Source: Coherent Market Insights (2023).

The largest application of agar is within the food and beverage sector, but there is rapid growth in the pharmaceutical and nutraceutical sectors. Currently, there is a large demand for agar from both North America and Europe. The South American region is smaller and slower growing, but it does reflect the same dominance of the food and beverage market, with rapid growth expected in the pharmaceutical and cosmetics areas (Mordor Intelligence n.d.-b). The largest agar market within the South American region is Brazil.

The key players operating in the agar market have a strong focus on quality and include Agar Sari Jaya, Agar Swallow Indonesia, Gino Biotech, Hugestone Enterprise, Justchem International, Meron, Pt. Agarindo Bogatama, Pt. Kappa Carrageenan Nusantara, Pt. Surya Indoalgas, and Roland Foods.

Figure 6. Chicken with a seaweed-based sauce. Photo credit: TNC.

Belize Production and Markets for Red Seaweeds

Three main seaweed species are farmed in Belize: *E. isiformis*, *Gracilaria crassissima*, and *K. alvarezii*.

Figure 7. Top: *E. isiformis*. Middle: *G. crassissima*. Photo credit for top and middle: Seleem Chan, TNC. Bottom: *K. alvarezii*. Photo credit: Md. Simul Bhuyan, Wikimedia Commons, CC BY-SA 4.0.

E. isiformis is a species of red algae in the family Solieriaceae (Figure 7). It is grown for its relatively high carrageenan content (approx. 60% of the salt-free dry weight; Guist *et al*. 1985). This seaweed has rapid growth in the spring and then ceases to grow in the summer; it develops tetraspores in the fall and then goes through sporulation, followed by disintegration of the mature plants in the winter. The spores germinate the next spring. On average, the *E. isiformis* cultivated in Belize reaches 24-30 cm after 90 days (TNC unpublished) and is an excellent source of iota-carrageenan. In Belize, it can be found near Glovers Reef and other sites on the Belize Barrier Reef Complex.

G. crassissima is among the species in one of the genera that comprise the greatest numbers of species in the family Gracilariaceae (Rhodophyta), with the majority of them reported in warm water and tropical regions. Currently, the genus *Gracilaria* is the major worldwide agar source (Freile-Pelegrín and Murano 2005), as it can contain approximately 25% of dry weight (Yudiati *et al*. 2021).

K. alvarezii is a red alga native to the Indo-Pacific. Its live color is actually green or yellow. It grows rapidly, doubling its biomass in 15 days, and is able to reach 2 m, providing a harvest cycle of 100-120 days. *K. alvarezii* has been introduced throughout the warm tropics for commercial cultivation. It is a major producer of kappa-carrageenan, which is used for medicinal purposes and as a homogenizer in milk products, toothpaste, and jellies (University of Hawaii n.d.). The carrageenan content can be up to 35% of dry weight (Pong-Masak and Sarira 2020). It is cultured in more than 20 countries and remains confined to farm areas in much of its range, but it also has the potential to behave as an invader. (For more information about *K. alvarezii*, see the appendix.)

International records (FAO 2023; Table 2) of live weight (wet) red seaweed production from Belize began in 2012, with an average annual production of 4380 kg valued at USD 8760 annually and a corresponding average price of 2.0 USD/kg.

The main products sold on the local Belize market are dried seaweed, powdered seaweed, and value-added products for human consumption and for skin and hair care. Dried products are sold for between USD 10 and USD 20/lb (USD 22 and USD 44/kg).

Table 2. Belize red seaweed production from 2012 to 2021.

Variable	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Wet weight production (kg)	3600	1000	2200	3000	3000	3000	4000	5000	5000	5000
Dry weight production (kg) *	324	90	198	270	270	270	360	450	450	450
Value (USD) for wet weight	7200	2000	4400	6000	6000	6000	8000	10,000	10,000	10,000
Price (USD/kg)	2	2	2	2	2	2	2	2	2	2

Note. Source: FAO (2023).

* Dried seaweed is normally sold on the local market. Assuming a conversion of 11:1 from wet to dry seaweed, one-eleventh, or 9%, of wet weight remains after drying (Future of Fish 2023).

Seaweed powder and assorted value-added products (beverages, gels, creams, soaps, etc.) normally cost between USD 5 and USD 10. Some powdered seaweed products may be sold for up to USD 50/lb (USD 111/kg; Future of Fish 2023).

A preference for using *Kappaphycus* for beverages and food products and *Eucheuma* for some value-added products has been indicated. However, a price differentiation has not yet emerged between the two cultured species.

More investigations are needed into the nutritional value and composition of extracts from these species. *Kappaphycus* is known to have high-quality carrageenan compared to *Eucheuma*. Prices are likely to change as seaweed products diversify, market development continues, and product information becomes more widely available in Belize. The current prices reflect the total demand primarily in and around the main production centers and population centers. These areas include experimental farms located off the coast of Placencia in Southern Belize and within the Turneffe Atoll Marine Reserve located off the coast of Belize City, beyond the Barrier Reef.

Dried seaweed is the most common product on the local market. It is often converted to powder or gel form and is used to make beverages, ice creams, and general food ingredients for local dishes. The local market also consists of a small number of individual buyers, mainly women involved with nonfood value-added products, such as gels, powders, and infused forms (seaweed mixed with other ingredients) used to make cosmetic, skincare, and haircare products (Figure 8). These individuals purchase between 2 and 4 lb (0.9 and 1.8 kg) of dried seaweed each month, which they process to make these specialty seaweed products, usually at their homes. These value-added products sell for prices ranging between USD 5 and USD 15. Most people involved are entrepreneurs between 30 and 40 years old with less than 5 years of involvement in the industry and varied educational and socioeconomic backgrounds.

Figure 8. (1-4) Selected value-added seaweed products from Southern Queen Products. Photo credit: Reena Beverly Usher. (5) Sea Gold Essentials powdered seaweed in capsules. (6) Mother Nature Enterprise facial scrub. (7) Seaweed Powa seaweed salad. (8) Eucheuma Belize infused seaweed gel. (9) Natural Seaweeds (Beverage & Gels) seaweed shake. Photo credit for #5-9: the Belize Trade & Investment Development Service (BELTRAIDE). (10) Seaweed Powa pepper sauce. Photo credit: Seleem Chan, TNC.

Future Market Potential for Belize Seaweeds

Beyond the small amounts of dried seaweed, powdered seaweed, and value-added products used for human consumption and for skin and hair care, the Belize seaweed industry has shown an interest in identifying expanded markets to support growth. In assessing the potential for future markets for Belize seaweeds, export food markets were not included in this report, as the Belize infrastructure is fragmented, and little opportunity currently exists to provide fresh or dried seaweed that meets the external regulatory standards for export.

Two emerging markets for seaweed products and extracts lie within the bioplastics industry and the markets for biostimulants, fertilizers, and soil regeneration. Most export markets are expected to continue to request clean, dried, and relatively unprocessed seaweed products due to the highly specialized secondary processing facilities needed to extract their required components. However, in the future, once additional markets are scaled, it might be possible for Belize to consider local, perhaps community-based, facilities to enable extraction, which would increase the potential value of Belize seaweed and products.

Bioplastics

Seaweed polysaccharides have been shown to be able to provide bioplastics in a film form and have been beneficial for green production methods (Seaweed Packaging. n.d.; Patel *et al*. 2019; Lim *et al*. 2021). While the majority of bioplastics currently on the market are not seaweed-based, the bioplastics market is driven in part by innovation from companies like Notpla (www.notpla.com) that have had recent global success with their seaweed-based coatings for food containers, winning the Earthshot Prize (The Earthshot Prize 2023) and continuing their rapid growth as a company and product maker (European Bioplastics 2023).

At present, bioplastics represent only 1% of the annual global production of plastic (Center for International Environmental Law. n.d.), but the demand for bioplastic products is rapidly increasing, as are the numbers and diversity of bioplastic applications and products. Just over half of the bioplastic materials produced are biodegradable (including polylactic acid [PLA], polyhydroxyalkanoates [PHAs], and starch blends).

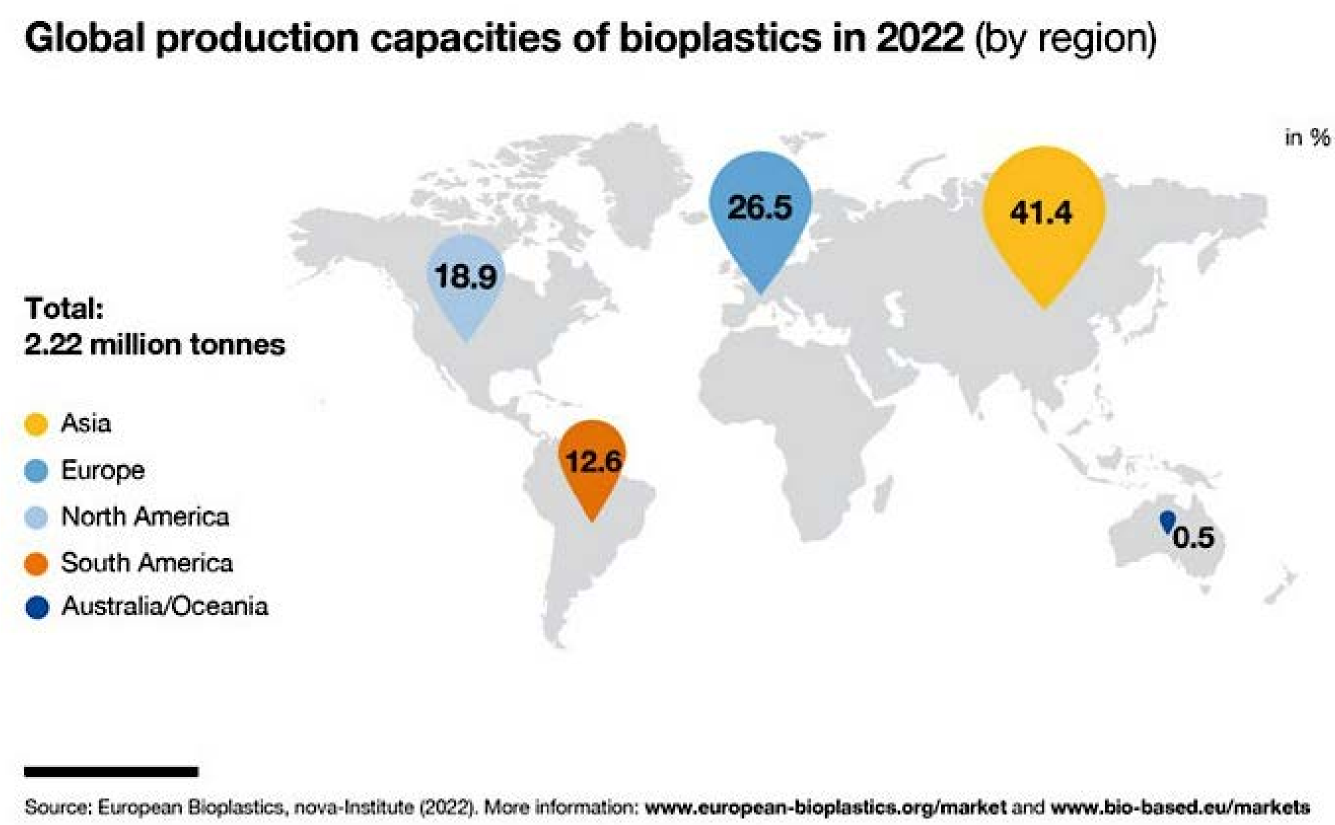

Figure 9. 2022 global production capacities for bioplastics. Source: European Bioplastics (2023).

Current capabilities for global bioplastic production are centered in Asia and Europe (Figure 9), where countries such as France have been leading the way in banning single-use plastic from food outlets (Tucker 2023). The European Union has been instrumental in creating restrictions limiting plastic pollution by banning products such as plastic food containers, plastic bags, and cigarette butts (European Commission n.d.). Demand for bioplastics also exists in North America and South America, though, providing potential local export markets for Belize. The North and South American bioplastics markets are set to grow rapidly, particularly for flexible packaging, which is a type of bioplastics particularly well-suited for seaweeds (Waters *et al*. 2023).

In South America, government policy has significantly driven bioplastics utilization, and legislation limiting the use and distribution of single-use plastic is being developed. In various nations, products such as plastic bags and drinking straws have already been banned, and new legislation is reducing several types of unwanted plastics. Several industries are replacing plastics in packaging due to legal restrictions and changes in customer habits. For example, iFood (www.ifood.com.br), the Brazilian market leader in online food ordering and delivery, has committed to reducing the amount of single-use plastic it provides to its consumers. The South American bioplastics market is currently larger in terms of revenue than the North American market and is projected to more than double, from USD 2.596 billion in 2020 to USD 5.349 billion by 2027 (Knowledge Sourcing Intelligence 2022).

Biostimulants

Biostimulants are agricultural products made using plant hormones, seaweed extracts, enzymes, microorganisms, and trace elements. These plant biostimulants are applied to seeds, soil, the leaves of cereals, grains, fruits, vegetables, oilseeds, and other plantation crops. They assist in promoting sustainable agricultural practices and enhancing crop productivity by reducing the use of fertilizers. They also increase antioxidants in plants and minimize environment-induced stress. Moreover, they help preserve the ecological balance of nature by boosting metabolism, nutrient intake, water retention capacity, and chlorophyll production (IMARC Group n.d.).

The global market for seaweed extract biostimulants is expected to grow significantly from 2023 to 2030, with a growth rate of 12.9%, and is expected to reach USD 2581 million by 2030 (Data Bridge Market Research 2023). The main market driver is the rising need for sustainable agricultural practices. Consumers are increasingly seeking out organically produced foods for ethical and nutritional reasons. Their preferences, in turn, create demand for seaweed and natural product-based biostimulants.

In South America, the overall biostimulants market reached USD 389.2 million in 2022 and is expected to grow to USD 785.2 million by 2028, exhibiting a large growth rate similar to that of the global market. Seaweed extract biostimulants held the largest market share in South America, amounting to 51.8% of the total market in 2022, which was a consumption volume of 26,500 tonnes and was worth USD 199.9 million. The high demand is theorized to be due to seaweed biostimulants exhibiting improved overall plant health, stress tolerance, root growth, nutrition and water intake, plant growth, and crop yield. Seaweed extracts have been shown to improve nutrient uptake and translocation in crops such as maize, oilseed, rapeseed, tomato, wheat, and soybean (Mordor Intelligence n.d.-c).

Globally, market drivers and consumer concerns vary but align strongly with a need for greater sustainability within product sourcing and creation, which could provide a strong market opportunity for Belize seaweed. The large market share that seaweed biostimulants already hold in South America could be especially fruitful for Belize due to its geographic proximity to potential future markets.

Seaweed Supply Chains, Regulations, and Certifications

Seaweed management and the value chain structure

The seaweed industry in Belize is considered to be at a low developmental level in terms of output, production systems, and the efficiency of its value chain. Value chain efficiency requires a set of enabling policies and legal instruments that allow each actor to maximize their contribution, including adhering to social responsibilities and conserving ecological functions (Porter 1985). In Belize, the primary actors along the seaweed value chain include producers (farmers); entities that provide basic processing and storage (postharvest handling); buyers for human consumption, exports, and value-added products; and the final consumers (Figure 10). These primary actors are supported by several indirect actors, including international NGOs, government regulators, conservation practitioners, academia, and market factors that drive the production system and supply chain.

Managing the seaweed industry primarily falls under the mandate of the Belize Fisheries Department, overseen by the Ministry of the Blue Economy and Civil Aviation (MBECA). The department is responsible for marine fisheries resources and the conservation of marine ecosystems. The main policy and legal instruments are the Fisheries Resources Act 2020 and the National Fisheries Policy, Strategy, and Action Plan (2020-2024) developed in 2019. They address processes affecting the seaweed industry, such as licensing and data collection, sustainable livelihoods, research, experimental fishing, and other activities concerning mariculture and seaweed.

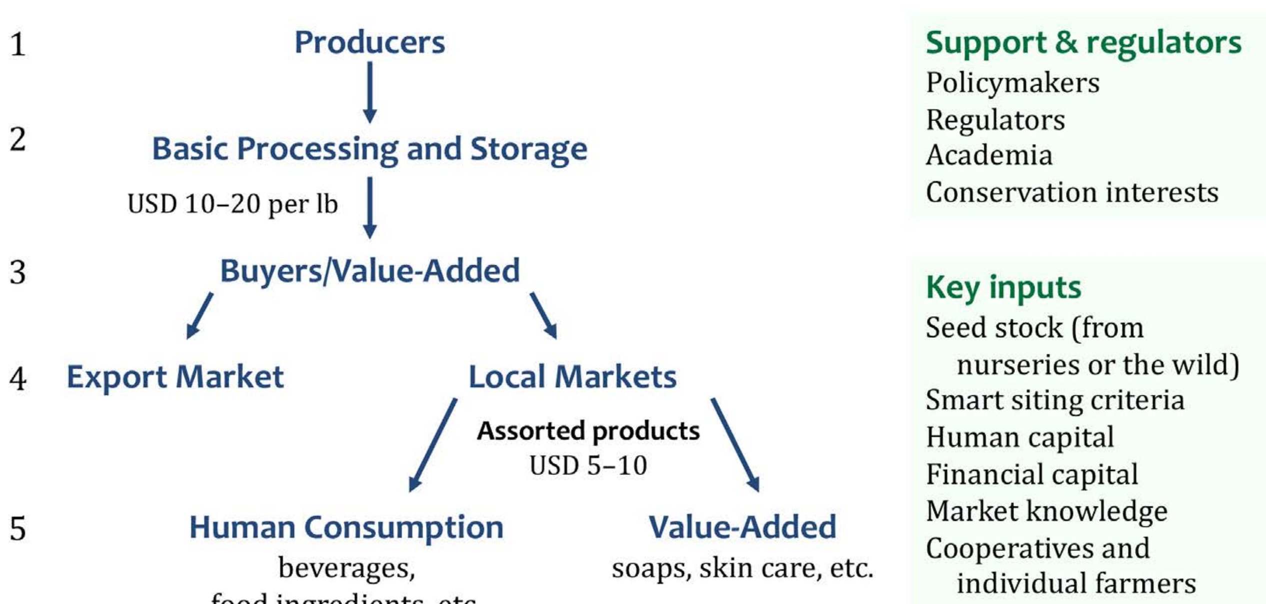

Figure 10. Summary of Belize's seaweed value chain, including primary actors, support, and key inputs.

The absence of specific policies and legislation to govern and develop the Belize seaweed industry has led to several value chain inefficiencies over the years due to duplication, overlap, and fragmented responsibilities among the several government agencies. Led by TNC, efforts continue to address these issues to improve management practices and develop legislation supporting seaweed's sustainable production, consumption, and value-added development in Belize.

As an example, TNC has provided financial and technical support in partnership with BELTRAIDE and Turneffe Atoll Sustainability Association to initiate the formulation of the Belize Mariculture Policy 2022, which the Belize government endorsed in February 2022. This policy seeks to provide a structure and clear direction to improve the efficiency of the seaweed industry, and it outlines several principles and priority areas on which future regulations should be based. These include:

- Adjustments to the regulatory framework
- Strengthening of the institutional framework
- Standards, market development, and access
- Capacity-building
- Sustainable approaches to development

The Mariculture Policy 2022 is intended to complement existing instruments aimed at developing the production system and supply chain. Noteworthy instruments include the Environmental Protection Act 2000, Revised Edition 2011; the Coastal Zone Management Act 2000, Revised Edition 2011; Belize Port Authority Act 2003, Revised Edition 2011; Standards Act 2000, Revised Edition 2011; and National Lands Act 2003, Revised Edition 2011 (Table 3).

Other important legal and policy initiatives have been implemented to improve the efficiency of the current value chain and governance to ensure the sustainability of the Belize seaweed industry. These include the updated Fisheries Resources Act 2020 and the first seaweed Best Management Practices (BMP) documents, which were developed in the context of the overexploitation of some fisheries resources due to increasing demand, declining stocks, and ecological degradation, as well as the need to manage the interests of other important sectors, such as tourism.

These legal and policy initiatives aim to support sustainable and equitable livelihoods, community development, and an ecosystem-based approach to developing the sector and providing the opportunity to diversify livelihoods in coastal communities. Initiatives also aim to develop and promote sustainable practices, generally in mariculture and specifically in seaweed mariculture.

Seaweed demand and sustainability

The local demand from seaweed buyers in Belize is driven by its health benefits. As mentioned earlier, seaweeds are rich in compounds such as iodine, copper, iron, calcium, Vitamin C, Vitamin B12, Vitamin K, and several essential amino acids that are the building blocks of protein. They are also the source of high-value hydrocolloid carbohydrates, such as agar, alginate, and carrageenans, which are extracts that have applications for food production and other industries. A high consumption of seaweed is said to be associated with high life expectancy, exemplified by Japanese people, whose life expectancy is among the highest in the world (Ferdouse *et al*. 2018). These factors have increased the interest in seaweed products in Belize, especially over the last decade, reflecting the increasing global trend.

Table 3. Primary Belize seaweed value chain actors and selected policies and legal instruments governing their roles (not exhaustive).

Value chain actor	Role	Applicable regulatory legal instrument
Producers	Sustainable production of seaweed	
	• Licensing and permitting; mariculture definition	• Fisheries Resources Act 2020
	• Standards, quality, and labeling	• Standards Act 2000, Revised Edition 2011
	• Smart farm siting and safe use of maritime space	• Fisheries Resources Act 2020 • Belize Port Authority Act 2003, Revised Edition 2011 • National Lands Act 2003, Revised Edition 2011
	• Zoning and use of the seabed	• Coastal Zone Management Act 2000, Revised Edition 2011 • National Lands Act 2003, Revised Edition 2011
	• Environmental impact assessments, effluent management, marine and coastal pollution, and invasive species management	• Environmental Protection Act 2000, Revised Edition 2011 • Fisheries Resources Act 2020
Storage and processing entities	Storage of raw seaweed and basic processing	
	• Maintain product quality and health standards; labeling	• Standards Act 2000, Revised Edition 2011 • Belize Agricultural Health Authority (BAHA) Act 2003
Purchasers, value-added producers, and exporters	Local and foreign wholesalers of raw seaweed and value-added products	
	• Retail and production of wholesome and healthy seaweed products market	• Shops Act, Revised Version 2020 • BAHA Act 2003 • Customs and Excise Duties Act 2019 • Fisheries Resources Act 2020
Consumers	End users of seaweed and seaweed products for human consumption or other uses	
	• – –	• None

The importance of seaweed sustainability

The growing interest and demand for seaweed presents an opportunity to promote sustainable consumption and production (SCP) in Belize and adhere to environmental and social responsibility. Sustainable Development Goal (SDG) 12 — ensure SCP patterns — envisages environmental sustainability and economic development utilizing healthy products that can create decent jobs and ensure a healthy life (UN [United Nations] 2015). The Sustainable Development Goal 14 — conserve and sustainably use the oceans, seas, and marine resources for sustainable development — emphasizes, among other things, the conservation of marine life and the sustainable use of marine resources for economic development.

Belize's national goal of developing its Blue Economy aligns with the abovementioned SDGs. Seaweed buyers and consumers are becoming increasingly eco-conscious and desire more healthy, wholesome products like seaweed. Belize can put in place the framework for implementing important SCP actions for seaweed, such as ensuring food safety, developing sustainable management systems, and advancing social and environmental responsibility, that will support a sustainable value chain with access to the most important and lucrative markets. Critical to this developmental process will be identifying the main challenges related to seaweed buyers and value-added product development and utilization.

Figure 11. Fish swim near coral off the coast of Belize. Photo credit: TNC.

Buyers should consider the sustainable or unsustainable sourcing of seaweed. Information must be widely circulated to ensure greater public understanding and buy-in for sustainable seaweed production practices. This would allow buyers to understand the adverse impacts of unregulated harvesting of wild seaweed species, which can lead to overharvesting and further depletion of wild seaweed stocks.

In addition, many juvenile aquatic organisms use seaweed as their home or place of refuge; hence, directly removing seaweed affects these creatures. Natural seaweed beds function as nursery habitats for a multitude of commercial and noncommercial species, such as the Caribbean spiny lobster (*Panulirus argus*; Figure 12), the channel clinging crab or Caribbean king crab (*Mithrax spinosissimus*), finfish like the mutton snapper (*Lutjanus analis*), and echinoderms like the sea cucumber (*Holothuria Mexicana*).

Figure 12. A juvenile spiny lobster nestled in seaweed. Photo credit: Seleem Chan.

Seaweed is susceptible to storms and pathogens, and overharvesting increases the possibility of population collapse. Given the significant ecological contribution of seaweeds, a collapse would also mean the loss of ecosystem benefits, such as nutrient sequestration and carbon sequestration. Without nutrient and carbon sequestration, eutrophication (or increased acidification) can occur. For these reasons, it is recommended that markets focus on farmed seaweed, which may involve wild-harvesting in order to seed farms or nurseries but not for direct sales or markets. Buyers are tasked with ensuring that high-quality and sustainably produced seaweed is sourced from certified producers.

Environmentally conscious consumers are often willing to pay higher prices for products labeled as organic or sustainable. For many, the first indication of sustainably sourced products is labeling. Larger consumers, such as retailers, may also be interested in ensuring products are sourced sustainably to avoid reputational risk and to meet customer requirements.

Ultimately, purchasing only sustainably cultivated and harvested seaweed ensures a three-tiered benefit: social, economic, and ecological. The social component is included, given that marginalized individuals, such as women and youth, are treated equally and are given the opportunity to develop new skill sets.

Challenges for seaweed buyers and value-added product development

In general, the developmental challenges faced by the seaweed industry in Belize require strengthened legislative, regulatory, and institutional structures (discussed in the *Belize Seaweed Industry Technical Guide*, a companion to this situation analysis). This is also the case regarding local buyers and people involved with value-added products. The following list of challenges was informed by a comprehensive literature review as well as interviews with local actors; these are the main areas identified:

Inconsistent supply quantity and quality – While seaweed production in Belize appears to be generally increasing, the quantity supplied at a given time is inconsistent with local demand. This imbalance has led to difficulties obtaining adequate supply for direct consumers and people involved with value-added products. The quality of seaweed supplied has also been reported to be inconsistent, which may be related to the inherent differences between the two main cultivated species: *Eucheuma sp*. and *Kappaphycus sp*. For example, members of the Belize Women's Seaweed Farmers Association have suggested that there are minimal differences in the food and beverages made using either species but noticeable differences in gel consistency and the texture of value-added products used for hair and skin care.

Lack of production standards – Regulators and NGOs like TNC have worked over the years to develop and promote best practices for seaweed production. However, there is a need to adopt formal production standards specific to the seaweed industry that are supported by enforced regulations and monitoring and evaluation programs. These regulations and programs are necessary to ensure seaweed production and utilization are sustainable and to conserve the marine ecosystems where they are grown.

Lack of quality standards – The current informal state of the industry in Belize is reflected in the lapsed postharvest handling, storage, food safety processing, and packaging of seaweed products available for consumptive and non-consumptive uses. This issue is related to product quality and can affect the ability to access markets in the future.

Lack of specific regulations and regulatory standards – The current governance framework used for the Belize seaweed industry is inadequate to support the current and future development of the seaweed value chain. Important developments, including the Mariculture Policy 2022 and the ongoing drafting of regulations, will hopefully address important gaps. The Mariculture Policy has noted inefficiencies in the current regulatory framework, which have led to the replication, fragmentation, and duplication of responsibilities. This situation is compounded by a general lack of resources and policy clarity to effectively carry out the roles of different actors along the value chain (see Table 3 for a list of roles). The situation has also proved difficult for stakeholders wishing to enter the industry.

Lack of formal product research and development – Closer collaboration is needed among entrepreneurs, regulators, conservation interests, and academia to support a greater level of product development to meet the needs of current and prospective markets. Current value-added product ideas often lack the content analysis, packaging, labeling, and traceability requirements needed to access certain marketplaces. While BELTRAIDE and others have worked to develop the business structures of individuals and groups involved in the seaweed industry, more needs to be done on product development to access niche markets for high-quality, sustainably grown seaweed products. There is also the possibility of accessing markets for carbon-reduction products, such as biostimulants and bioplastics, which have high carbon sequestration potential. A strategic seaweed research agenda is needed to support value chain actors and ensure Belize can take advantage of these sustainable opportunities.

Poor understanding of industry processes and support structures – Buyers and people involved with value-added products have reported that industry processes are unclear, including where and how to access support services from either government agencies or private organizations. As an example, those wishing

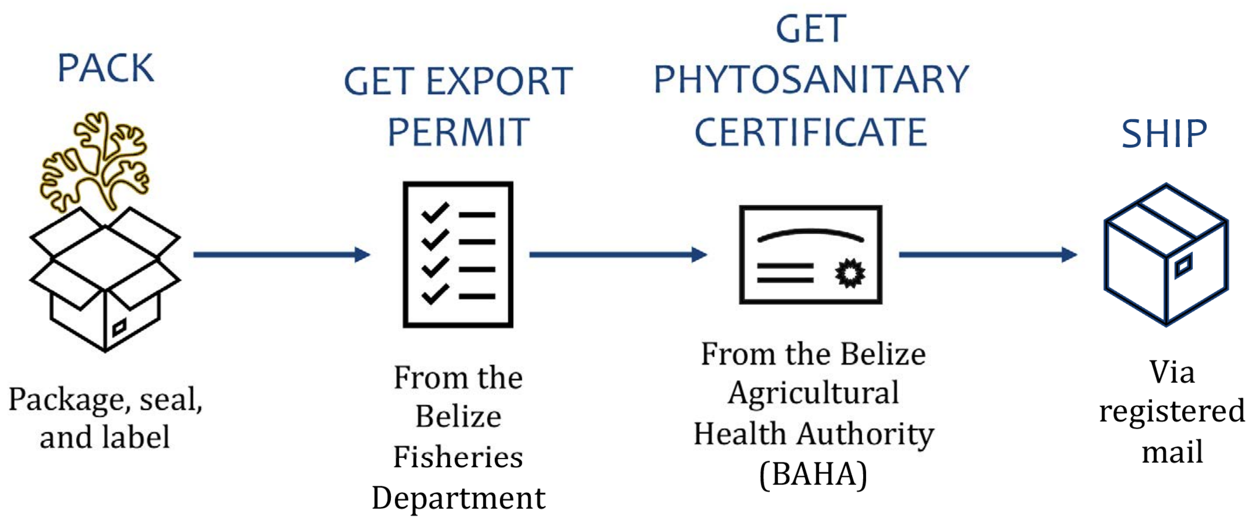

Figure 13. Summary of the current export process for small parcels of seaweed (less than 5 lb, or 2.27 kg).

to access export markets have described a lack of information on the packing requirements and approvals needed to export even small packages of dried seaweed. Yet, BELTRAIDE has facilities and arrangements to assist business development, including accessing subsidies. Many people are unable to take advantage of this assistance because they are either informal entities unregistered with the government or simply unaware that these services exist.

Addressing buyer supply and value-added product development challenges

Several options may be considered exclusively or adapted to address the challenges specific to the Belizean context for improving the environmental, economic, and social sustainability of the seaweed supply and value-added product development. It should be noted that the following list is not meant to be exhaustive but rather presented as options with different levels of viability. The decision on how to proceed in addressing these challenges will depend on the national context and management objectives. It would be prudent, however, for decision-makers to consider a broad set of the most important environmental, economic, and social variables that can reduce the risks associated with each option.

Information toolkit for seaweed value chain actors – Developing an information toolkit that clearly outlines the roles and responsibilities of value chain actors, as well as important processes such as obtaining permits and clearances for export, can help improve the understanding of the industry. Such a toolkit could be included in new or existing training programs and could, for example, outline the process for exporting seaweed (Figure 13) and registering a seaweed business.

Purchasing from reputable farms – In the short term and in the absence of regulations and SCP standards, seaweed buyers should purchase from reputable farmers, preferably from those whose operations are located in designated farming areas, have registered their business with the authorities, and have received the training that follows the best management and production practices, such as those promoted by Belize Fisheries Department, TNC and the National Seaweed Working Group.

Interestingly, in the fall of 2023, the price paid by buyers was not identified as a challenge or drawback. Generally, there was a positive attitude toward seaweed and a willingness to pay for seaweed and seaweed products because of the belief that seaweed is a wholesome food and a source of high-quality cosmetic products. This positivity may be evidence of dormant demand for seaweed. Once these supply challenges are addressed and seaweed can be reliably and safely supplied to markets, people seem to be willing to pay for the products. Buying sustainably grown seaweed will be important to maintaining the trust of end consumers as well as supporting the ecosystems from which these products come.

Mariculture parks – These parks are designated marine spaces that have been mapped, zoned, and allocated for specific mariculture purposes and for specific resource users. Mariculture parks have been proposed as a model for sustainable mariculture production, including seaweed, to promote the vertical integration of actors along the value chain. Mariculture parks are akin to industrial parks on land and may be part of a larger national marine spatial plan (MSP), with designated marine protected areas (MPAs) to protect biodiversity and sensitive areas. The idea is similar to the land-based concept, where basic infrastructure and support services for production, processing, storage, transport, and marketing are provided. In this way, small-scale artisanal producers can achieve economies of scale, reduce individual risk, take advantage of collective competitive advantages, and facilitate better knowledge and technological transfer. The best example of this concept is in the Philippines; the bulk of its seaweed is produced through mariculture. The country has implemented several such parks that have led to supply chain benefits. Belize could leverage the organizational structures of existing cooperatives and seaweed farmer groups, as well as the MSP that is already in process. These tools could be adapted to the Belize context using the lessons learned in the Philippines to avoid any pitfalls. Important challenges encountered by the Philippines mariculture parks included increased stakeholder conflict, increased risk of pollution, increased risk of diseases, predial larceny, and sometimes high costs. These can be mitigated or addressed in the early stages of the industry so that Belize can realize the best possible outcome. Buyers of seaweed and value-added products could benefit from the increased quantity and quality of production and increase the possibility of meeting local demands as well as accessing export markets.

Management, consumption, and production standards – Developing a comprehensive set of standards for the Belize seaweed industry can be a long-term solution to address buyers' supply issues and facilitate the development of value-added products. These standards would consider each value chain actor, allow for improved industry management and regulation standards, and improve SCP practices, food safety management, and traceability. Achieving these standards will require detailed and targeted assessments of the value chain and its socioeconomic and environmental impacts to inform the standardization processes. Significant capacity development will be required for agencies such as the BAHA, the Belize Bureau of Standards, the Belize Customs and Excise Department, the Belize Fisheries Department, and other key regulatory actors along the value chain. These agencies are critical in implementing, monitoring, and evaluating said standards, which will need to be strengthened by enabling legislation and additional infrastructure.

Due to the developing nature of most countries' seaweed industries, few international standards are recognized for seaweed management, SCP, food safety management, and traceability. However, it is possible for Belize to adopt private or international third-party standards or to develop its own. National standards may or may not be developed based on third-party standards; either way, this approach has the advantage of responding to the local context.

In the short to medium term, as Belize continues to develop its seaweed industry, developing related national standards and adopting best practices may provide the best way to address the challenges faced by buyers and value-added producers. As previously mentioned, these standards and best practices must be accompanied by legislation, capacity-building, and infrastructure. As such, there are several benefits and trade-offs that would need to be weighed against the previous options outlined (Table 4). Among the most important benefits of developing national standards and best practices are those listed in the last row of Table 4.

For example, the Philippines used this approach, developing national seaweed standards and the Code of Good Aquaculture Practices (GAqP; BAFS [Philippine Bureau of Agriculture and Fisheries Standards] 2021), including the mariculture of seaweed. This process was initiated in 2018 to avoid technical barriers to markets after the Aquaculture Stewardship Council (ASC) and the Marine Stewardship Council (MSC) jointly developed the ASC-MSC Seaweed Standard (ASC-MSC 2018). The Philippines is the fourth-largest seaweed producer globally, with over 1.5 million tonnes (Cai *et al.* 2021).

Deciding how standardization is pursued in Belize will depend on the national policies and developmental goals regarding seaweed. Also, cost, economic viability, and the specific needs of target markets are important considerations, along with buyer and consumer preferences for seaweed and its products. It will also be important, especially during this developmental stage of the seaweed industry, to limit or prohibit imported seaweed products to avoid endangering local production and the pursuit of a sustainable seaweed supply chain.

Table 4. Analysis of selected options for implementing management, consumption, production, and food safety standards for the Belize seaweed industry.

Standardization option	Examples	Benefits ("pros")	Trade-offs ("cons")
Private international seaweed standards	The **ASC-MSC Seaweed Standard** was jointly developed by the ASC and MSC in 2018. **Ecocert** is a certification body that provides organic certification for various products, including seaweed-fed lamb and skincare products. **Friend of the Sea** is a global standard for	Promote environmentally sustainable and socially responsible seaweed production. Are open to both cultured and wild-harvested seaweed operations worldwide to demonstrate sustainability. Promote ecosystem health (structure, productivity, function, and diversity of the ecosystem) and social responsibility.	Are costly to implement, as independent third-party conformity assessment bodies are required to audit them. Have been met by very few entities. May require a cost-benefit analysis and other analyses before being considered.

Standardization option	Examples	Benefits ("pros")	Trade-offs ("cons")
	seaweed products and services for companies that practice sustainable seaweed production while conserving marine habitats.	Promote minimal negative consumption and production impact. Promote more efficient management (decision-making, planning). Provide a baseline for improvement. Allow access to high-end market opportunities. Include chain-of-custody procedures for traceability.	May require additional infrastructure and legal arrangements to assess chain-of-custody processes. May require additional infrastructure.
General international SCP standards	**ISO 22000:2018**, a 2018 standard from the International Organization for Standardization (ISO), is specific to food safety management systems (FSMSs). It considers key elements along the food and value chain to identify and address food safety hazards and traceability.	Have long track records of supporting national policy, regulatory frameworks, and best practice guidelines for production systems and value chains. Are widely recognized and accepted auditing criteria. Consider the holistic development of value chains and supporting systems, including food safety, sustainable management systems, environmental responsibility, and social responsibility. Are widely recognizable and accepted by international markets and consumers.	Are often cumbersome and difficult to understand and implement. Include cost as a key barrier to the implementation of an effective and sustainable FSMS. Require regulatory and institutional structures and prerequisites. For example, implementing the Hazard Analysis Critical Control Point (HACCP) system requires having prerequisite programs operating according to national regulations, codes of practice, or other food safety requirements.
National standards and best practices	The 2021 national standard in the Philippines is **PNS/BAFS 208:2021, Seaweeds – Code of Good Aquaculture Practices (GAqP)**. This standard (BAFS 2021) was developed in response to MSC-	Are based on local needs and context. Provide the opportunity to combine elements from different private and international standards.	May not be accepted internationally. May require additional regulations, infrastructure, and capacity-building.

Standardization option	Examples	Benefits ("pros")	Trade-offs ("cons")
	ASC developments and to defend the seaweed industry from potential technical barriers to trade. The United States has mandated that unprocessed seaweed comply with the general requirements of the **Federal Food, Drug, and Cosmetic Act** regarding preparation, packaging, and sanitary conditions.	Allow for the development of local production, regulation, and institutional capacities. Offer the opportunity to define local indicators for monitoring and evaluation. Provide the foundation for adopting the more rigorous standards of lucrative markets. Offer the opportunity to develop inclusive standardization processes that are more likely to receive stakeholder buy-in. Allow for established minimum requirements for value-chain actors that align with management goals. The requirements would address regulation, production, harvesting, post-harvesting, food safety and quality, seaweed health, environmental health, and social responsibility.	

Traceability challenges in Belize

Although seaweed has been harvested in Belize over the last 4 decades and cultivated over the last decade, no seaweed traceability system has been used. Such a system is needed not only to ensure products are sourced from certified producers but also to track each farm's productivity levels. Tracking these levels will help guide future modifications to the methods and managerial aspects of seaweed farming. However, tracking from a producer-only standpoint does not necessarily guarantee sustainability.

Despite the industry's size and the possible challenges in implementing a traceability system in its early development stage, a tremendous opportunity exists to establish proactive models and schemes. These models will aid in ensuring social, environmental, and financial sustainability. Sustainably produced goods can often access high-value niche markets that noncertified products cannot, such as the health food segment. Belize may not have large retail stores, but the local market represents a high-value niche.

Hence, the vision is for newly implemented traceability systems to position Belize's seaweed in the health food market and similar. The traceability system would be for three levels:

1. Producers
2. Processors — e.g., beverage vendors and restaurants
3. End consumers representing the value chain's final step and mainly driving market demand for sustainably produced products.

PART 2

Potential Environmental Benefits and Impacts of Seaweed Farming in Belize

As marine conservation in Belize becomes increasingly significant, so does the conservation of stakeholder livelihoods. For more than 4 decades, traditional Belizean fishers have been harvesting native red, edible seaweeds from the wild — namely, *Eucheumatopsis isiformis* and *Gracilaria crassissima*. While little of the extant literature details the impacts of farming activities on the ecosystem, it is known that there can be negative impacts if these activities are not monitored. On the other hand, restorative seaweed aquaculture offers considerable benefits when farmed well.

While the Belize seaweed industry is still in its initial development and has had a relatively low environmental impact, the opportunity exists to implement conservation measures that will protect the marine ecosystem and the services it provides. This section discusses the ecological and social impacts of seaweed farming and enables protected-area managers, law enforcement officials, and other conservation stakeholders to make informed decisions about the spatial suitability of seaweed farming. Doing so will ensure the sustainable development of seaweed mariculture while achieving livelihood development, ecological conservation, and restoration goals and while engaging in research and regulations that protect sensitive areas and species that could be impacted by a growing industry.

Social and Ecological Benefits of Seaweed Aquaculture

Seaweed mariculture is increasingly seen as a sustainable economic activity that can also yield significant environmental and social benefits. It has emerged as a strategy for restorative aquaculture, defined as aquaculture practices that can provide direct ecological and conservation benefits to the ecosystem and can potentially generate net-positive environmental outcomes (TNC 2021).

Developing the seaweed industry in Belize has several important benefits to marine conservation and addressing the negative impacts of climate change. These include restorative seaweed mariculture, which has the potential to generate ecosystem services (Gentry *et al.* 2020), including:

- Carbon sequestration
- Climate change mitigation
- Water quality improvements
- Habitat enhancement and restoration
- Alternative livelihoods
- Socioeconomic and cultural services

However, the effectiveness of a seaweed mariculture system in providing these ecosystem services will depend on several key factors (TNC 2021), which include but are not limited to culture species, farm scale and design (e.g., Figure 14), farm management practices, cultivation gear, and local environmental conditions.

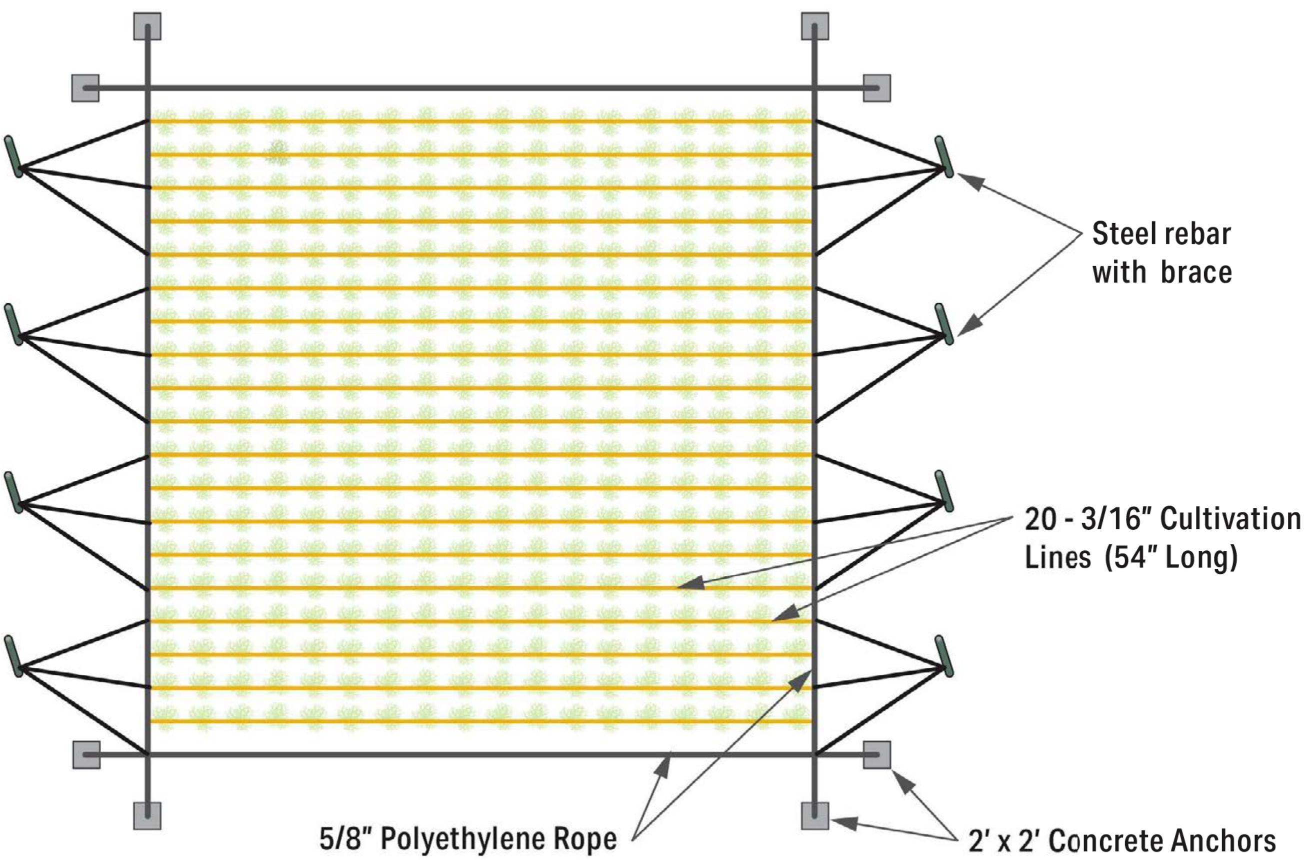

Figure 14. An example of a design for a submerged seaweed farm. Image credit: Jim Kopp.

Monitoring key performance indicators, like water quality, species abundance and diversity, and carbon sequestration rate at the farm level, is important to develop and monitor farm performance in providing these ecosystem services. See TNC's [monitoring, evaluation, and learning framework](#) (2024) for more information. Below, the set of ecosystem services that can be provided by seaweed mariculture, according to Gentry *et al*. (2020), are discussed in further detail.

Carbon sequestration and climate change mitigation

Through photosynthesis, growing seaweed absorbs carbon dioxide and, indeed, provides some carbon sequestration benefits. Under the right ocean conditions, seaweed fronds and particles will break away from the farms and can sink and be buried under the farm or be transported to the deep sea, where the carbon is sequestered in the sediment (Duarte *et al.* 2017).

Over the last decade, there has been debate about whether seaweeds and their farming sustain a significant, manageable carbon sink. It has spurred a critical analysis of how these ecosystems might be included in policy frameworks, as well as their use as a motivator for conservation and restoration. A more detailed understanding of the future of macroalgal carbon is required, both at local and global scales. Validating macroalgal carbon sequestration necessitates fully accounting for all carbon fluxes between the oceans and the atmosphere. Scientists have yet to agree on the right methodology to define the amount of underwater carbon captured through seaweed (Pessarrodona *et al*. 2023).

The capacity of seaweed to absorb large amounts of carbon dioxide through photosynthesis has led to increased calls for it to be included in climate change mitigation strategies. Removing excessive carbon dioxide from seawater reduces the effect of ocean acidification due to climate change, which can destroy the calcareous shells and skeletons of shellfish and corals.

Alternatively, the intentional use of the harvested seaweed biomass to produce materials could provide climate benefits more clearly (Jones *et al*. 2022). Major carbon benefits may also come from the potential for seaweed-based products, such as bioplastics and biostimulants, to replace fossil-fuel-based products (Waters *et al*. 2023). Seaweed farms can be seen as an alternative to some land-based production systems that require extensive land area and the removal of natural vegetation. In this way, seaweed farms have the potential to be a net-zero carbon industry since production is largely associated with very low emissions. Meanwhile, its biomass can be used in biofuels, biochar, bioplastics, etc.

The emerging markets for products such as biostimulants, biofuels, and bioplastics may represent an important future climate mitigation strategy that can incentivize seaweed production. While much more needs to be done to develop these markets to become economically viable, its potential as a sustainable climate strategy is strong when seaweed products are swapped out for products that produce higher carbon emissions and use significantly more resources.

Water quality improvements

Seaweeds are very efficient at absorbing nitrogen, phosphorus, and other elements from seawater. Seaweed naturally removes nitrogen and other elements by incorporating them into their tissue. As a result, seaweed farms have the potential to absorb excess nutrients that cause eutrophication, thus improving water quality in coastal areas. Nitrogen is a nutrient that enters coastal waters from many human sources, including fertilizers, septic systems, and treated wastewater. Coastal marine environments are often affected by an influx of nutrients from nearby land use activities from urban areas, agriculture, and industries. Excess nitrogen fuels excessive algal growth, which can result in algal blooms that negatively affect water quality and human health. Reduced nitrogen and eutrophication can improve water quality, leading to enhanced ecosystem functions and the survival of important blue habitats, such as coral reefs and seagrass beds, that support nurseries and growout areas for adult marine species. Research by TNC suggests that a single hectare (10,000 m^2) of restoratively farmed seaweed can remove more than half a ton (0.45 tonnes) of nitrogen a day (Theuerkauf *et al*. 2022).

On a localized scale, seaweed aquaculture has been shown to buffer the impact of ocean acidification (Unsworth *et al.* 2012). Ocean acidification reduces the amount of carbonate in the water, making it harder for calcifying organisms, such as shellfish or coral, to form their shells and skeletons. For example, by co-culturing seaweed and shellfish, the seaweed could create a buffered halo effect and improve the water quality for growing shellfish. Or, by siting a large seaweed farm upstream of a reef, the down current flowing over the reef could potentially reduce dissolved carbon dioxide and increase the pH of the water and thus improve water quality for the benefit of the reef (Jiang *et al*. 2013). Moreover, improvement in water quality can lead to extended preservation of other blue carbon habitats, like seagrass meadows, which also sequester carbon.

Habitat enhancement and restoration

Seaweed farms have been shown to increase habitat complexity, enhance biodiversity, and restore other ecosystem functions caused by natural disasters or destructive practices, such as the overharvesting of wild seaweed. When farms are properly located, seaweed aquaculture can provide habitat for other fish and invertebrate species (e.g., Figure 15), thus restoring biodiversity. Dense seaweed fronds provide three-dimensional structures that create refuge, breeding, and reproductive grounds for marine species, including fish, invertebrates, sea birds, turtles, and marine mammals.

Figure 15. Jacks swimming among the cultivation lines of a submerged seaweed farm. Photo credit: Seleem Chan, TNC.

Consequently, creating seaweed farms can provide the same ecosystem function as natural nursery grounds, allowing juvenile fish and invertebrates to hide from predators and reach maturity (Theuerkauf *et al.* 2022). Aside from structural benefits, these organisms and biofouling communities associated with farms can provide food resources for other marine life in the area (Lu and Li 2006). The outcome is higher biodiversity on the farms. In TNC's global review of 65 studies, greater fish abundance and diversity were generally noted around seaweed (and bivalve) farms compared to nearby reference sites (Bossio *et al*. 2021). The researchers found that the abundance of wild fish increased by up to 5 tons (4.54 tonnes) per year around 1 ha (10,000 m^2) of restorative aquaculture farming compared to reference farms. TNC research has found that seaweed farms in Belize serve as juvenile nurseries and habitats for commercial finfish, lobsters, and conch.

The increased habitat complexity, improved water quality, reduced local temperature, and reduced local ocean acidification provided by seaweed farms can have restorative or enhancing effects on marine ecosystems. These habitat conditions promote the resources needed for the ontogenetic development of various marine species, contributing to the overall resilience of the ecosystem.

Alternative and supplemental livelihoods

From a societal standpoint, restorative aquaculture offers supplemental livelihoods for coastal communities in ways that can complement traditional fishing livelihoods in many coastal regions. Beyond that, they can create supplemental economic opportunities where coastal communities struggle as a result of fish stock collapses. For example, in the small fishing village of Placencia, fishers turned toward seaweed farming many years ago as a supplemental livelihood approach. The seaweed farms, in turn, provided habitat for commercially important conch and lobster species depleted in the wild, providing further spillover benefits to the local fishers, similar to MPAs. In cases where livelihoods have been negatively affected by climate change or unsustainable practices, seaweed mariculture can be a supplemental or alternative livelihood for communities.

Socioeconomic and cultural services

Tourism, fisheries, marine transport, and other coastal economic and cultural activities are directly and indirectly linked to ecosystem services, such as the provision of beaches, coastal protection, clean oceans, fish stocks, coral reefs, and coastal wetlands. Restorative seaweed mariculture strategies can therefore contribute to conserving marine coastal ecosystems while developing sustainable livelihoods for coastal communities.

Additionally, seaweed is considered a wholesome food source that can provide nourishment for coastal communities (e.g., Figure 16), leading to better human health outcomes. Thanks to their high nutritional value, seaweeds are healthy components of human diets, providing a rich source of proteins, essential amino acids, and vitamins and minerals, such as iodine, potassium, and iron. All of these are necessary for ensuring a properly functioning body and helping mitigate the risks of various diseases (Ferdouse *et al*. 2018). Thus, developing the seaweed industry can contribute to food security and supplemental livelihoods for fishers while reducing the pressure on other marine species.

Figure 16. Seaweed stew with chicken. Photo credit: Seleem Chan.

Conservation challenges — the impacts of seaweed mariculture

Marine resource conservation and sustainable development is a worldwide challenge. The UN 2030 Agenda's SDG 14 — conserve and sustainably use the oceans, seas, and marine resources for sustainable development — provides the framework for addressing the challenges associated with marine resource conservation at the national and local levels (UN 2015). Among the main challenges to achieving this SDG is ensuring that best practices in production and utilization are adhered to while addressing the issues of poverty, gender equality, livelihood development, and reducing inequalities (Troell *et al.* 2023). Sustainable mariculture, including seaweed, has been identified as an important contributor to achieving the SDGs.

Sustainable seaweed farming is generally associated with low environmental impacts compared to other forms of culture (Sugumaran *et al*. 2022). However, challenges and risks are associated with seaweed mariculture, and conservation practitioners and managers alike must consider them (Eggersten and Halling 2021). They include:

- Shading the seafloor, causing direct negative impacts
- Increasing competition for local marine flora
- Inadvertently trampling the underlying marine vegetation at seaweed farms, potentially destroying key nursery and adult habitats for many species
- Serving merely as fish aggregation devices without providing or enhancing marine habitats
- Potentially introducing species that become invasive
- Potentially permanently modifying habitats
- Establishing new pests and diseases
- Enhancing negative effects due to climatic and oceanic changes

At the global level, the socioeconomic frameworks and structures for mariculture are still in development. As a result, many developing countries face challenges with achieving sustainable production and utilization, leading to inequalities and difficulties in accessing markets and capital for product development, especially for marginalized groups (Troell *et al.* 2023). In such environments, the risk of stakeholder conflict increases with seaweed farmers and other users of the marine space, such as fishers, tourism interests, shipping, and conservation. Effective consultation and the use of informed site selection methods will be vital.

Opportunities for the Belize Seaweed Industry

The early developmental stage and the socioeconomic profile of the Belize seaweed industry present several opportunities for directly addressing the challenges faced, namely, those related to governance, production, socioeconomic development, and environmental conservation. Conservation practitioners, resource managers, government regulators, academics, and other stakeholders will be key to ensuring that these challenges are overcome and that the industry grows sustainably.

In a general sense, seaweed mariculture has the potential to greatly benefit conservation, resource development, and academic research together. It is part of one of the fastest-growing blue foods sectors. It has been suggested that seaweed mariculture meets national and international SDGs because of specific advantages related to the following:

- **Low cost of entry –** Mariculture is generally associated with low start-up costs compared to other livelihood activities.
- **Gender equity and youth engagement –** Mariculture is still relatively new in many parts of the world. This early stage presents the opportunity to equitably develop legislation and development strategies that fully engage women in livelihood activities as well as educate and solidify sustainable practices and attitudes among youth who may become part of the value chain in the future.
- **Alternative and supplemental livelihood –** Seaweed culture has proved to be a sustainable and economically viable alternative and supplement for livelihoods in coastal communities.
- **Conservation tool –** Seaweed mariculture has been used as a conservation tool at the local level to reduce fishing pressure, provide supplemental livelihoods, provide nursery habitat for marine life, improve water quality, improve biodiversity, and enhance habitat complexity for maintaining ecosystem services.
- **Climate adaptation and mitigation strategy –** The resilience of ecosystems and coastal communities is an international priority under the UN Vision 2030 (published in 2015 as Resolution A/RES/70/1). Developing sustainable livelihoods and conserving ecosystems through activities involving seaweed mariculture offer important avenues for building resilience against the negative impacts and uncertainties caused by climate change.

  Seaweed also absorbs carbon, nitrogen, and phosphates efficiently from seawater, combating both ocean acidification and eutrophication.
- **Development of MSPs –** The development of seaweed mariculture, which is still new in many parts of the world, presents the opportunity to develop management and decision-making tools, such as MSPs, value chain assessments, stakeholder consultations and education, monitoring and evaluation plans, and others that can have wide-reaching developmental implications. MSPs, for example, are useful not only for mapping areas for mariculture but also for assisting other sectors, such as marine conservation, tourism, transport, and fisheries.

Developmental context of Belize seaweed

Belize's small population density, socioeconomics, and relatively large marine ecosystems present several challenges and opportunities for conservation and sustainable development. In general, the use of natural resources or production systems may undergo four distinct stages over time depending on the management scheme. These stages include the following (Perissi *et al*. 2017), as shown in Figure 17:

1. underdevelopment
2. rapid expansion and capitalization
3. overexploitation
4. stabilization

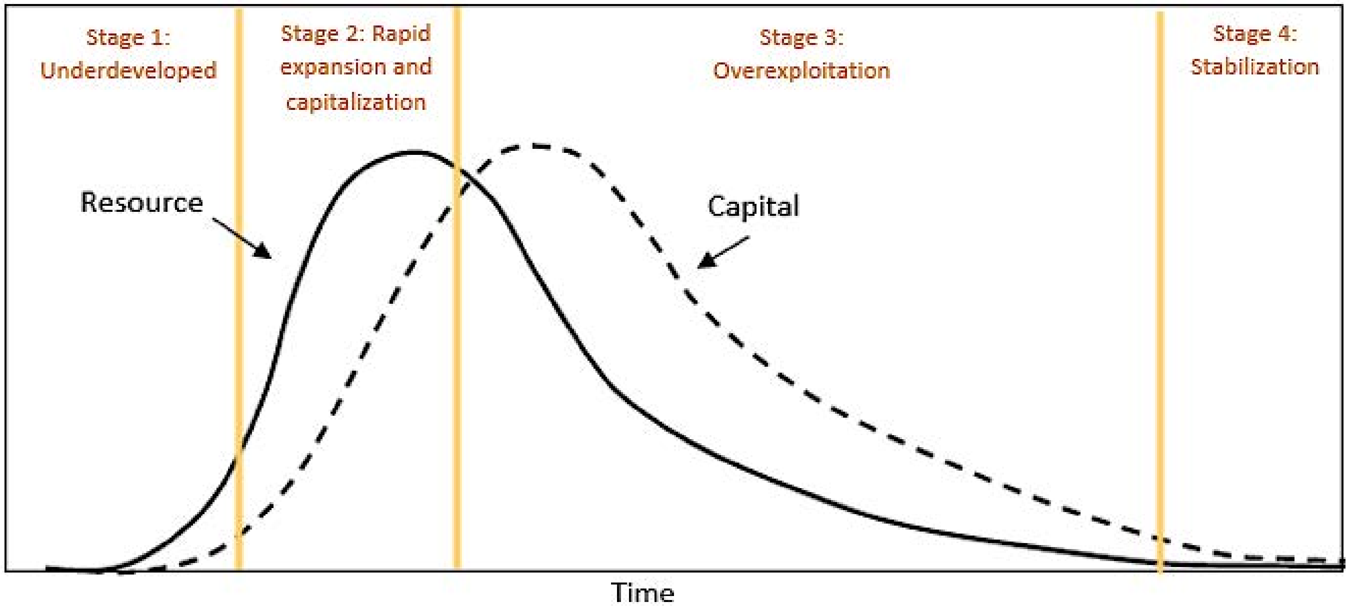

Figure 17. Generalized model of the developmental stages of a fisheries production system: (1) underdevelopment, (2) rapid expansion and capitalization, (3) overexploitation, and (4) stabilization (Perissi *et al.* 2017).

Underdeveloped production systems (Stage 1 in Figure 17) may refer to the subsistence use of a resource before knowledge of markets, technologies, and the size of the resources are understood for large-scale production. In this phase, management is often reactive, but negative impacts on the environment are negligible due to the low levels of exploitation. As knowledge increases over time, the stage of rapid expansion and capitalization occurs, characterized by increased productivity and capital investment. The threat to the natural environment may increase due to the additional demands placed on it by the production system. Proactive and adaptive management interventions can address these negative effects if already in place. In the absence of such interventions, the system may enter an unsustainable stage of overexploitation, characterized by decreased production efficiency and a high risk of negative environmental impacts. Stage 4 (Figure 17) is stabilization, where a natural equilibrium is reached based on the carrying capacity and main system parameters at that given time. Notably, this equilibrium may be at a point of collapse or at a positive, sustainable level, depending on the level of management implemented.

The Belize seaweed industry is in the initial underdeveloped stage of its production system based on the state of its current production, governance, and socioeconomic profile. This designation can be an important consideration when conservation practitioners, resource managers, government regulators, and academics assess their roles in addressing the challenges and taking advantage of the opportunities it provides. It is also important to recognize the specific challenges and opportunities faced by the Belize seaweed industry. The main challenges facing the development of the Belize seaweed value chain are related to sustainable primary production, governance, value-added development, and markets.

Main Challenges for Conservation and Management

Production

The sustainable production of seaweed that preserves ecological systems and ensures socially equitable economic development remains a major challenge for Belize. The main stakeholders, including farmers, the government of Belize, and NGOs like TNC, have developed the production technologies and basic structures of the value chain over the years. Still, several gaps remain.

Initial costs

At the level of the farmer or entrepreneur, high initial costs prohibit many small and medium enterprises and individuals interested in seaweed from entering the industry. In large part, the industry's development was intended as an alternative livelihood for fishers and as a way to conserve marine stocks. The main producers and target group for support were male fishers who already had the means to set up farms on the offshore cays of Belize. A new farmer may find it difficult to set up and maintain a farm without the means to transport and secure the necessary equipment and people.

Lack of technical knowledge and support

A total of 97 stakeholders from across Belize have been trained in methods for sustainable seaweed cultivation, with 35% being women. Training and technical support continue to center around operators in the two main experimental production areas — Placencia and Turneffe Atoll. While the negative impacts are not believed to be significant as yet, a future expansion of the industry could result in unsustainable practices. Therefore, these challenges must be met and solved at this early stage to ensure a smooth transition from an immature to a mature stage of the industry.

Figure 18. A closeup photo of three people standing on a boat tying cultivation lines. Photo credit: Sarah Aly. Photo credit: Sarah Aly.

Environmentally destructive production practices

While there is no evidence of substantial damage to ecosystems due to seaweed farming in Belize, the government of Belize, through the Fisheries Department and NGOs like TNC, has proactively invested in training, building capacity, and sensitizing farmers on sustainable best practices for seaweed production. The government's interventions include, among others, permits and manuals from the Fisheries Department and TNC, respectively, outlining rules and recommendations for preventing damage to seagrasses, corals, and mangroves; managing debris; employing culture systems; implementing maintenance techniques; and securing equipment in case of events such as hurricanes. These interventions are intended to preserve the integrity of the ecosystems in which the primary production takes place and to prevent potential conflict with other users of the coastal waters in which seaweed farming is practiced.

The traditional twisted-rope method and the floating bamboo culture method have also been phased out in recent years. The former used floating devices made of plastic bottles and Styrofoam, which can potentially degrade, releasing microplastics, or may loosen and join other sea garbage or be mistaken for food by marine animals. Using bamboo as floats required cutting bamboo forests, potentially leading to soil erosion and other issues.

Overreliance on support for production

Despite the various forms of support for production, business development, marketing, and more that have been given to actors along the value chain, some people and farms are yet to achieve independence and profitability without substantial support. This overreliance on support is evident from the complaints of consumers and value-added people about the scarcity of the seaweed supply, suggesting that production is not meeting local demand. The two main production areas — Placencia and Turneffe Atoll — have received a great deal of support. Still, these areas may not be seeing the required investment from individual farmers to become independent, profitable, and capable of meeting local demand and, potentially, overseas demand. The industry also has commercialization limitations, which can be a factor as to why individual farmers are not investing significantly in their farms.

Standards, traceability, and consistency of supply

In Belize, formal standards along the seaweed value chain are lacking, ranging from primary production, processing, value-added products, permits and licenses, regulations, and markets. Important initiatives, such as the new Belize Mariculture Policy, capacity-building and training, and the development of BMPs supported by TNC, are important steps in the right direction. However, formal, basic, enforceable standards and traceability requirements are needed, with support from regulations. These standards would support best practices related to sustainable production, product quality and consistency, environmental stewardship, social equity, and governance to meet the desired market's demands. The lack of formal standards can be a significant barrier to developing the local value chain and can deny access to potentially more lucrative export markets. For example, value-added products will require consistency in quality and quantity.

Monitoring and evaluation

Developing a standard for actors along the value chain necessitates a system for monitoring their ecological, social, and economic impacts. The absence of a program for monitoring and evaluating key indicators denies all actors an important decision-making tool for ensuring that production standards, environmental standards, and market requirements are met. Therefore, monitoring and evaluating key environmental, production, governance, and market indicators are important in informing the industry's sustainable development.

Underdeveloped governance and institutional structures

An underdeveloped governance and institutional framework underlies all the challenges facing sustainable production in Belize and its utilization in meeting the demands of current and potential markets. This germinal framework is largely due to the lack of seaweed-specific regulations needed to enable all actors along the value chain to maximize their contributions to the industry. Many processes are inefficient and ill-defined, such as siting farms, obtaining licenses and permits, acquiring technical assistance, acquiring subsidies, and exporting products. Responsibilities for these processes fall under several agencies, most of which are not yet empowered by strong seaweed-specific regulations and lack the necessary resources. In the export process, for example, no test exists to identify different seaweed species in powder or gel form. Due to this lack of technical and institutional capacity, exporters may be unable to take advantage of overseas market opportunities. This and similar governance issues along the value chain have resulted in inefficiencies in production, stymied value-added development, caused overlaps and fragmentations in institutional responsibilities, and increased the risk of stakeholder conflict.

The recent development of BMPs and the Belize Mariculture Policy 2022, supported by the Fisheries Department and TNC, represents important steps toward improving the governance and institutional structures of the seaweed industry. They have provided the basic framework for drafting regulations specific to seaweed mariculture that, among others, will define the roles of actors and reduce some of the ambiguities that have resulted in the overlap, duplication, and fragmentation of responsibilities among regulators. The BMPs and Mariculture Policy have also provided the basic framework for developing important decision aids and monitoring and evaluation tools, such as detailed spatial management plans and value-chain monitoring and evaluation plans for ecological, social, and economic processes affecting the industry.

Guidelines for Conservation Practitioners and Managers

Conservation practitioners and government regulators play critical roles in the sustainable and equitable development of the seaweed industry in Belize. Belize's coastal and marine ecosystems are vulnerable to threats, such as climate change, the influx of nutrients, and unsustainable levels of illegal, unreported, and unregulated fishing. As such, the government of Belize has identified alternative and supplemental livelihoods, such as seaweed mariculture, as a priority for coastal community development and the Blue Economy.

Conserving marine ecosystems and their ecosystem services are key strategies of conservation practitioners for meeting international development goals like the UN SDGs, which speak to, among other things, tackling overfishing, protecting biodiversity and sensitive areas, and increasing science-based decision-making. Conservation NGOs, such as TNC, have taken the lead in developing the Belize seaweed industry in the last 15 years, with others, such as the Global Environment Facility – Small Grants Program and the World Wildlife Fund, also making important contributions. Through its seaweed aquaculture project, TNC has made monetary and non-monetary contributions to primary seaweed production, capacity-building, improved governance, and research to facilitate sustainable development. Government regulators, academia, and other key actors have also supported and benefited from these interventions.

Some notable events in this regard include the formation of the National Seaweed Working Group in 2016-2017, the establishment of training programs, environmental baseline studies, the establishment of seaweed nurseries, the development of governance and best management frameworks (2018), and the development of the Belize Mariculture Policy 2022 (see its vision and mission in the sidebar). The government of Belize and TNC have also laid the foundation for developing important policy and decision-making tools, such as an MSP. In 2022, as part of TNC's Blue Bonds for Ocean Conservation program — a financing mechanism for national conservation and climate goals for national debt relief — the first milestones for achieving this MSP were successfully achieved. Though not specific to the seaweed industry, the MSP will form a key part of the seaweed development and governance strategy in the future.

Despite these advances, the Belize seaweed industry remains in its infancy and will require closer collaboration among conservation practitioners, government regulators, academia, and other actors interested in sustainable development to plug knowledge gaps and remedy value chain inefficiencies. For instance, thus far, many of the interventions have focused on the environmental and production side of the seaweed value chain. While these are crucial elements, several technical and knowledge gaps remain that continue to stymie development along the chain. These include the areas of post-harvest handling, supply consistency, supply quality, standards development, processing, market requirements, access to export markets, regulations, and ambiguity in the roles of institutions along the seaweed value chain. Collaboratively addressing these areas will be important to providing a conducive environment for the industry's sustainable development and the conservation of marine ecosystems.

Belize National Mariculture Policy 2022

Vision

A sustainable and responsible mariculture sector that is consolidated as an effective contributor to Belize's Blue Economy and the food and nutritional security of the country.

Mission

Position mariculture development in the Belizean economy to meet growing demand for mariculture products and as a source of community livelihood, through strengthened regulatory and institutional frameworks, market and capacity development, and the use of climate-smart technologies and global best practices.

(Belize Fisheries Department and TNC 2021, p. 13)

Governance

Strengthening governance structures and related institutional development can provide tremendous opportunities for addressing the main challenges facing the seaweed industry. Among the key opportunity areas in this regard are the following:

- **Development of governance and institutional structures** – Developing best practices, policies, regulations, strategies, and standards, along with needed institutional and legal structures, can put foundations in place to ensure sustainability and improve the efficiency of the value chain as the resource is developed. Establishing these foundations will be important to avoid the pitfalls of rapid uncontrolled expansion, overcapitalization, and overexploitation. Developing improved interagency collaboration, research, and communication is also crucial to improving the value chain's efficiency. An opportunity now exists to address gaps in technical and institutional capacity to ensure long-term economic, social, and ecological benefits are maximized or aligned with national goals. Targeted regulations to accompany the Belize Mariculture Policy will need to be created to identify resources, empower agencies, and clarify their roles and responsibilities in the industry. It is important to highlight that strengthening governance structures could help address all other weaknesses along the value chain by empowering each actor or stakeholder to improve their output and contribution to developing the industry.

- **Development of standards and traceability –** The industry's relatively small number of actors presents an opportunity to develop local standards for primary production, processing, value-added products, permits, licenses, and regulations according to the current and expected market requirements. These can include developing the minimum requirements for licensing and permits, basic processing, and export.

  Establishing local standards for the seaweed industry allows Belize seaweed to distinguish itself in the marketplace as it seeks to prioritize quality over quantity. Such standards can also pave the way for meeting the often-stringent standards of the most lucrative international markets, such as those in Southeast Asia, the European Union, and the United States.

- **Planning and decision-making tools –** Baseline assessments, monitoring and evaluation programs, detailed market assessments, and MSPs, if implemented properly, can be key planning and decision-making tools. These can ensure that decisions made at the individual farm level up to the national government are based on the best available information. Several steps have already been made in this direction, including the initiation of the MSP process for Belize's marine space in 2022 under the Blue Loan and Conservation Funding Agreements. However, several gaps also exist, including national-level environmental baseline assessments and a comprehensive value chain assessment. It is important that these decision-making tools meet the needs of the targeted actors and are appropriate in scale to be applicable and useful.

- **Partnerships for development –** Developing interagency relationships and partnerships among local and international stakeholders can help improve social, economic, and environmental conservation gains. Establishing better cooperation among conservation practitioners, government regulators, academia, and markets can significantly streamline the processes along the value chain and ensure sustainable development of resources and products.

SWOT analysis

Figure 19 presents a strengths, weaknesses, opportunities, and threats (SWOT) analysis of the Belize seaweed industry geared at conservation practitioners and regulators, summarizing the previous sections of Part 2.

S Strengths

- Energetic and active stakeholders
- Strong focus on sustainable development and conservation
- Positive public perception of seaweed
- Strong interest from entrepreneurs
- Funding support available for value chain development

W Weaknesses

- Poor governance and institutional framework
- Underdeveloped regulatory framework
- Inefficient production system and value chain
- Production that is overdependent on support
- Limited baselines and standards
- Unreliable supply
- Limited processing and value-added
- Poor knowledge of market

O Opportunities

- Initial development phase
- Scope for improved governance
- Conservation and climate benefits
- Economics and social benefits
- High demand for seaweed products
- Low cost of entry
- Scope for targeted research and development of products

T Threats/ Risks

- Inaction by key actors/stakeholders
- High opportunity cost of inaction
- Marine and coastal degradation
- Loss of ecosystem services
- Loss of livelihoods
- Disenfranchisement of women and youth
- Decreased resilience of communities

Figure 19. SWOT analysis of the Belize seaweed industry, summarizing its main characteristics.

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Appendix

The report titled *SWOT Analysis for* Kappaphycus alvarezii *Cultivation in the Caribbean Sea*, which begins on the next page, has been inserted in its entirety as an appendix to this Belize situation analysis. The *K. alvarezii* SWOT analysis retains its original formatting, page numbering, and bibliography.

SWOT ANALYSIS FOR KAPPAPHYCUS ALVAREZII CULTIVATION IN THE CARIBBEAN SEA

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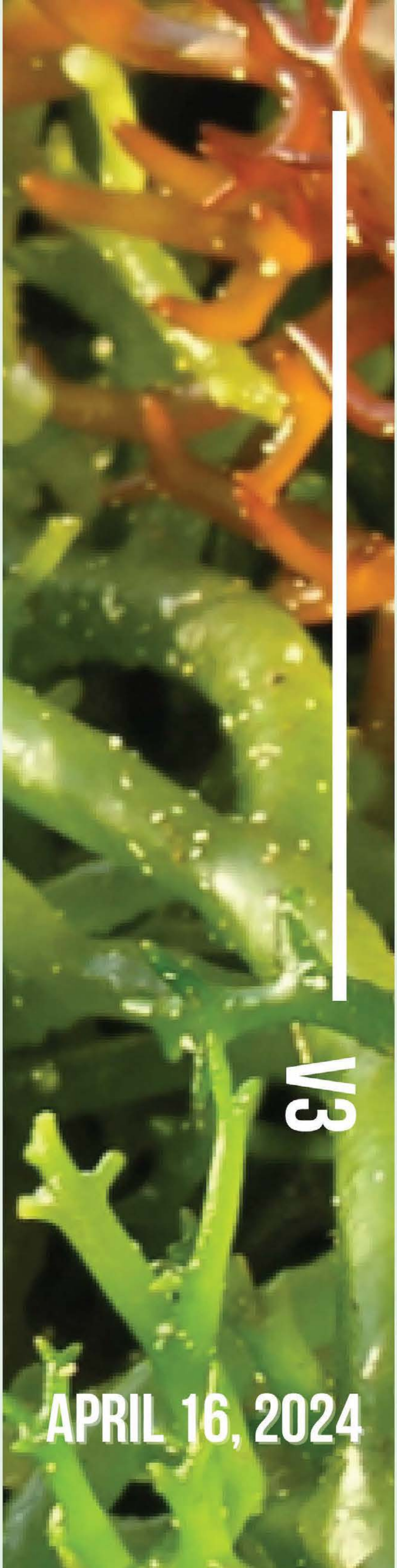

Introduction

Kappaphycus alvarezii[1] is a commercially important, red seaweed that is widely cultivated around the world to obtain feedstock for carrageenan production (Buschmann and Camus 2019). In 2020, *K. alvarezii* was ranked 5th among the world's most cultivated macroalgae (Rudke et al. 2020). *Kappapycus alvarezii* is native to the Philippines, but it has been introduced to approximately 30 other countries for either research or the development of a commercial seaweed farming industry (Ask 2020). Within the Caribbean, our region of focus, *K. alvarezii* is either currently grown, or has historically been grown, in Belize, St. Lucia, Mexico, Panama, Venezuela, and Brazil. In Caribbean countries and territories where *K. alvarezii* is currently grown, it is typically the most cultivated seaweed species. A specimen of *K. alvarezii* was also recently documented in Costa Rica, where the species is not currently cultivated (Cabrera et al. 2019).

The purpose of this document is to assess and report on the strengths, weaknesses, opportunities, and threats associated with *K. alvarezii* cultivation in the Caribbean as we currently understand them in 2024. To do this we first provide a brief introduction to *K. alvarezii* biology and farming practices, and the tendency of naturalized *K. alvarezii* to become invasive in some of the locations where it has been introduced. Then we dive deeper into which characteristics of *K. alvarezii* have led it to become an invasive species in some geographies where it has been introduced, and what the resulting impacts have been. We consider three management options for addressing the potential invasiveness of *K. alvarezii* in the Caribbean; providing recommendations for actions that both aquaculturists and marine resource managers can take and acknowledging that there are some potential risks associated with these actions. Lastly, we group and present the information gleaned from the SWOT analysis so it can serve as a go-to reference for further discussions and decision-making.

[1] Kappaphycus alvarezii is commonly referred to as 'cotoni' or 'cotonii' within the industry (Neish et al 2017). Some phycologists consider Kappaphycus striatum and K. alvarezii and to be the same species (Semesi, 1996).

Biology of Kappaphycus alvarezii and the socio-economic benefits associated with its cultivation

Kappaphycus alvarezii Doty (Solieriaceae, Rhodophyta) is a species of red marine macroalgae that is both cultivated, and found in reef ecosystems, around the world. It typically has thick, spiny branches (up to 2 cm in diameter) that occur in irregular (multi-axial) patterns and narrow to acute tips. These branches are densely covered with branchlets, typically ranging from 1 – 8 mm long. The coloring of *K. alvarezii* individuals can range between green, yellow-orange, red, or brown depending on the strain, nutrient content, and recent light exposure of the alga. In its native habitat, *K. alvarezii* is typically found in high-flow areas with limestone-rich rocky substrates or shallow reefs (Trono et al. 1992); although it has been found as deep as 48 meters below the water's surface (Weber 1913). *Kappaphycus alvarezii* exhibits the triphasic life history that is common for red algae (Doty 1987; Figure 1), however it can also reproduce through fragmentation (Figure 1).

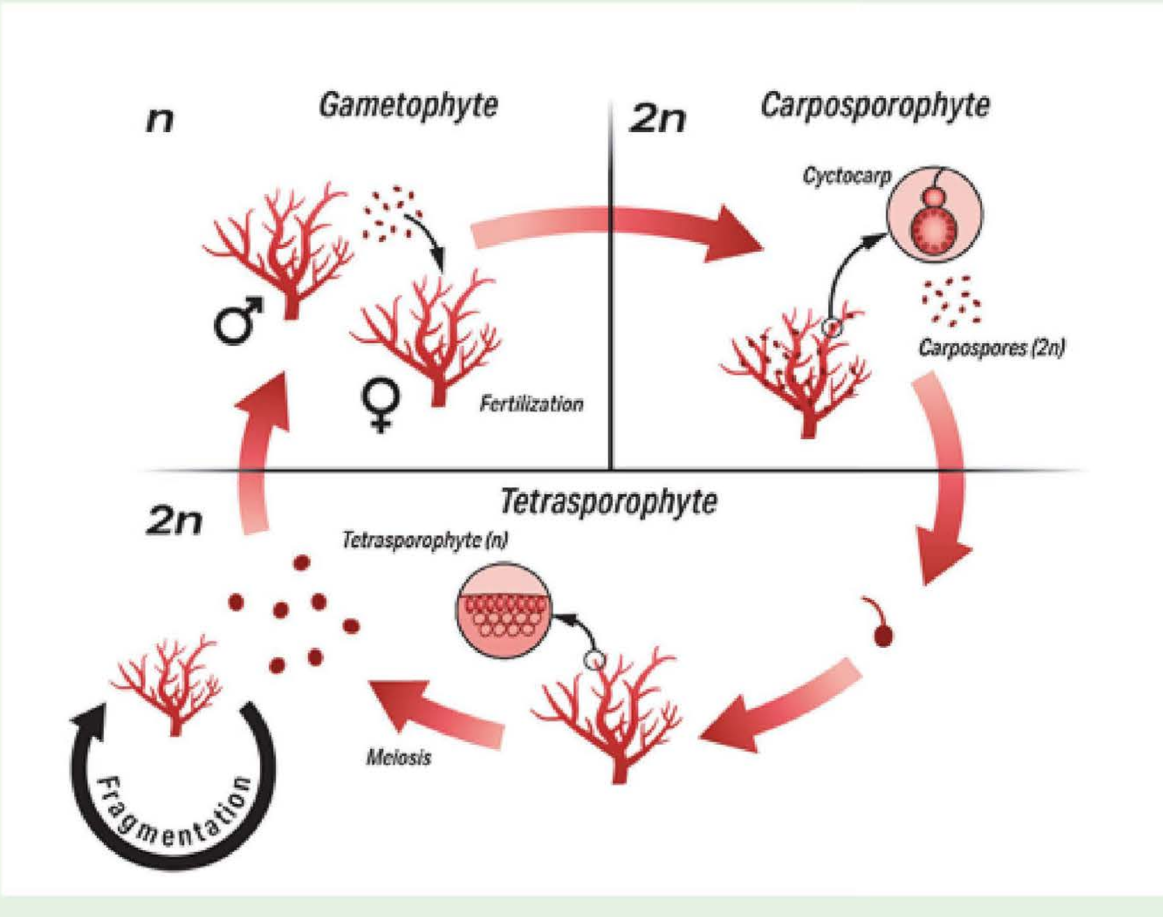

Figure 1. Kappaphycus alvarezii lifecycle.

To date, commercial farming of *Kappaphycus alvarezii* is completely dependent on reproduction via fragmentation. A mature, vegetative bunch is cut into smaller pieces, and then these pieces are raised to harvest size. This practice of using the same algal material for new outplanting is known as vegetative propagation or clonal propagation. Vegetative propagation means that the genetic diversity of the crop is never replenished; large portions of *K. alvarezii* crops likely originate from just a few clones. Over time this can be problematic because species survival, adaptation potential, and resistance to biotic and abiotic stressors is enabled by intra-specific genetic diversity.

As previously stated, *K. alvarezii* is an essential source of carrageenan, and more specifically kappa-carrageenan which is most used as a food additive to create firm, brittle gels, especially from dairy-based liquids. Kappa-carrageenan works especially well with dairy-based liquids. Across the world, over 1.6 million wet-weight tonnes of *K. alvarezii* are produced each year for carrageenan production (FAO 2022); and despite this large volume, the carrageenan market is still strong and supply limited. Ask et al. (2020) argue that the farming of Eucheumatoid seaweeds, a group that includes and is largely dominated by *K. alvarezii*, is one of only a few successful aquaculture opportunities for coastal villagers. They estimate that 40,000 – 50,000 families worldwide participate in the practice (Ibid).

Currently Caribbean-cultivated *K. alvarezii* is primarily grown and sold for either regional use, or exported for uses that do not include commercial carrageenan production. The most ubiquitous use of *K. alvarezii* regionally is in fruit-flavored shakes/smoothies, and in salads, which are sold locally at shops, village pharmacies, and fairs (Diez et al. 2019). Some entrepreneurs are also making artisanal soaps, shampoos, or facemasks that integrate seaweeds. The *K. alvarezii* that is dried and exported outside the region is either sold as is, or further processed into seaweed gels or nutritional supplements. Although Caribbean *K. alvarezii* production is extremely small in the global context, it does have the potential to provide supplemental or alternative livelihoods for both seaweed farmers and value-added processors.

Observed invasiveness of naturalized K. alvarezii, mechanisms, and potential impacts

In some of the locations where *K. alvarezii* has been introduced it is considered simply an *exotic* species, meaning that it has been moved from its original habitat range to a new one, but it is not yet reproducing in the new range. In other geographies, *K. alvarezii* is considered *naturalized*; enough individuals have been established that they are able to begin reproducing in the new range. This is the case in Tanzanian waters where *K. alvarezii* has been considered a naturalized species for some time, but signs of invasiveness have not been observed. Similarly, after 10 years of *K. alvarezii* cultivation in coastal waters of the state of Rio de Janeiro, Brazil, no signs of an invasion process have been observed (Castelar et al. 2009), perhaps due to specific environmental conditions that limit the development of propagules or viable spores (Cabrera et al. 2019). In regions where *K. alvarezii* has been naturalized, it is most found on patch reefs in shallow waters or inhabiting sand-covered grooves in the reef or the reef flats and edges (Rogers and Cox 2001). Along other coastlines, like those of Hawaii[2] and India, *K. alvarezii* has been designated an *invasive* species because it is causing ecological or economic harm to this environment where it is not native (Rodgers and Cox 1999; Conklin and Smith 2005; Arasamuthu 2023). Additionally, in Panama, *K. alvarezii* from abandoned farms has spread to the adjacent coral reef, seagrass, and mangrove ecosystems; forming benthic mats of 70+ m2 (Sellers, Saltonstall, & Davidson, 2014), but an official invasive species designation has not been issued yet.

Several characteristics of *K. alvarezii* make it a successful invader. To begin with, *Kappaphycus alvarezii* can spread by fragmentation, whereby pieces of seaweed float to new locations, and reestablish themselves. The recruit may remain vegetative, but it can also develop reproductive tissue.

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[2] Several additional dynamics may have led to the invasion success of *K. alvarezii* in Hawaii. The *K. alvarezii* introduced to Hawai'i is genetically distinct from all other cultivars (Zuccarello et al. 2006, Sellers et al. 2014). There has also been intense ecosystem change in the region and a lack of economic incentives (i.e. commercial production) that would otherwise possibly encourage the collection of *K. alvarezii* from reef systems (Ask et al. 2020).

Kappaphycus alvarezii has a high growth rate; under ideal conditions it can double in size in 15 - 30 days (Azanza-Corrales et al. 1992; Trono et al. 1992), and this growth rate is much faster than those of corals and many native seaweed species. The species also exhibits phenotypic plasticity in functional traits, which enables *K. alvarezii* to survive in a wide range of environmental conditions. For example, some specific strains of *K. alvarezii* can tolerate water temperatures ranging from 17 -32°C (Borlongan et al. 2017). However, *K. alvarezii* may not be as good as other Eucheumatoid species at sustaining respiration and other metabolic functions at temperatures over 32°C (Glen and Doty 1981).

If *K. alvarezii* invades an area, it can impact the functioning of nearby coral reefs and the marine organisms and people that rely on them. Because it grows faster than corals, *K. alvarezii* mats can overgrow and kill corals by shading them from sunlight (Arasamuthu 2023). In Southeast India, *K. alvarezii* was observed overgrowing live *Acroporan* corals; and in this region, the *Acropora* branching morphotype was found to be more commonly affected than other corals (Arasamuthu 2023). In Panama, *K. alvarezii* has been observed smothering or overgrowing *Porites* sp. and *Millepora alcicornis*[3] (Sellers et al. 2014). When corals are overgrown and die, this results in a shift from a diverse coral reef to a seaweed dominated, low-diversity reef. Substantial recruitment of *K. alvarezii*, or another seaweed species, can also change the bottom structure of the reef because the seaweed establishes itself in crevices and holes, which reduces the access that other marine organisms have to this habitat. Over time, these shifts in habitat availability and composition may impact commercial and recreational fisheries, and the attractiveness of dive sites used by operators bringing tourists to the area.

While the scientific community does not completely understand why naturalized *K. alvarezii* becomes invasive in some geographies and not others, the field of invasion biology has identified some general factors in host habitats that more commonly lead to successful invasions of aquatic primary producers.

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[3] Along with seagrass (*Thalassia testudinum*) and several species of sponges (*Clathria* sp., *Iotrochota* sp., *Ircinia* sp.) (Sellers et al. 2014).

Disturbed systems are generally more susceptible to invasion, as are systems that have lower biotic resistance provided by native macrophytes (Levine et al. 2004; MacDougall and Turkington 2005; Capers et al. 2007). These and other local habitat features interact with the biophysical traits of an alien species to determine whether excessive growth will occur (Alpert et al. 2000). As several factors are commonly required to co-occur in time and space to trigger invasiveness, time lags between the introduction of non-native species and the start of invasive behavior are common (Kowarik, 1995; Crooks, 2005). Given that *K. alvarezii* is already considered invasive in other locations, this suggests a high possibility that the aforementioned factors could combine to result in successful invasions of *K. alvarezii* elsewhere.

Fortunately, to our knowledge, the locations in the Caribbean Sea where *K. alvarezii* has been introduced have not already experienced an invasion. However, because there is potential for this to occur, and because the resulting impacts can be grave, we recommend that the precautionary principle be adopted by both individuals and organizations currently working with *K. alvarezii*, as well as resource managers responsible for overseeing the health and longevity of coastal areas. In the following subsection we introduce four management decisions to address the threat of a potential *K. alvarezii* invasion.

Management options and considerations for K. alvarezii in the Caribbean

In the Caribbean locations where *K. alvarezii* is already naturalized, the most effective and least-costly management options for potentially invasive species – introduction prevention, early-detection, and rapid-response (Hussner et al. 2017) – are not applicable. However, at least three other management decisions remain: 1) Status quo and increased monitoring, 2) Increased containment, or 3) Reduction, nuisance control, and potential eradication (Hussner et al. 2017). These decisions are presented in order of effort, and likely investment, required. In the following paragraphs, we provide a description of actions that would support each management option, as well as a discussion of the trade-offs associated with each.

1) Status quo and increased monitoring

The first option to apply the precautionary principle to *K. alvarezii* cultivation in the Caribbean is to continue the status quo, which includes small-scale *K. alvarezii* cultivation, while increasing monitoring of the farms and nearby coral reefs for *K. alvarezii* recruits. This decision might be partially justified with the knowledge of the ecosystem services that small-scale seaweed farms, including those growing *K. alvarezii*, provide. Well-managed seaweed farms have the potential to provide both provisioning and regulating ecosystem services. Seaweeds remove nutrients, minerals, and carbon dioxide from the water that surrounds them which works to maintain good water quality. Seaweed farms have been shown to compete with harmful algal blooms and opportunistic macroalgae like *Ulva* spp. for nutrients in the surrounding water (Valiela et al. 1997; Chopin et al. 2001; Neori et al. 2004). Additionally, by taking up carbon dioxide from the water, these seaweed farms can also help to alleviate the impacts of ocean acidification at a local scale. Seaweed farms also provide refuge or food for fish and other marine organisms; in most cases, tropical seaweed farms have a higher biodiversity and abundance of fish and invertebrates than sandy-bottom areas without seaweed farms or 3-D structures (Theuerkauf et al. 2021).

If farming *K. alvarezii* in the Caribbean is going to proceed as it currently stands, we recommend that it be combined with region-specific monitoring and invasiveness assessment efforts. One of the first steps would be to confirm the algal species that are being grown on each farm. In some cases, *K. alvarezii* can be impossible to distinguish from the native seaweed, *Eucheuma isiforme*, that is also purportedly grown throughout the Caribbean in small amounts. However, molecular techniques have been developed (Conklin et al. 2009) that would allow for samples from seaweed farms to be confirmed to the species level. Along with confirming the extent and location of *K. alvarezii* farming, additional monitoring on these farms could include careful documentation and reporting of reproductive material and suspected diseases.

Kappaphycus alvarezii may be a sleeper naturalized species that could become invasive if other is ecosystem dynamics shift, so it could be added to a watch-list for potential invasive species and monitored. Monitoring of reefs could be conducted by both citizen scientists and specialized researchers. Recreational divers and dive operators could be encouraged to submit suspected sightings of *K. alvarezii* to an online exotic species sitings program like the Reef Environmental Education Foundation (REEF) invasive species program. Specialized researchers could be asked to conduct a more thorough study to assess the invasiveness potential of *K. alvarezii* in specific areas. For example, a study in Brazil assessed the invasiveness potential of *K. alvarezii* at three sites in the Rio de Janeiro region by quantifying how much biomass was lost during farming activities, how much of this biomass re-established, and whether reproductive material (spores) were present on the re-established biomass (Castelar et al. 2009).

The status quo and increased monitoring management decision is appealing because it is the easiest option to implement, and it requires the least investment. It is akin to a "wait and see" approach, and this requires careful weighing against the risk that there could ultimately be a costly impact. The above-mentioned monitoring could help to detect a tipping point between *K. alvarezii* being naturalized vs. an invader, but marine invasions are sometimes hard to identify until the invasion is substantial and their impacts start to become widespread (Locke and Hanson 2009).

2) Increased containment

Adopting a containment and maintenance strategy for *K. alvarezii* would involve acknowledging that there are sites where *K. alvarezii* is currently cultivated or established in the surrounding ecosystem. Then a goal to prevent the spread of *K. alvarezii* from these locations to new ones could be set. The vectors and pathways for *K. alvarezii* dispersal must be disrupted in order to achieve effective containment of the alga. In the Caribbean, this primarily requires modifying existing seaweed farming practices, or establishing new ones.

To prevent new fragments of *K. alvarezii* from reaching and becoming established on coral reefs, farmers can use seeding, harvesting, and management techniques that minimize breakage of the seaweed propagules. Breakage of the propagules is more likely to occur with larger individuals (> 100 g) and when hauling heavier lines out of the water. Thus, working with smaller seed and harvest sizes may reduce loss of *K. alvarezii* to the environment. Another option is to consider harvesting in water via snorkel or SCUBA, rather than bringing the entire longline onto the boat or to shore, because the apparent weight of the propagules is much less in the water, so they are less likely to break. Farmers can also make an extra effort to look for, and collect, any *K. alvarezii* fragments in the water and off the seafloor surrounding their farms (Sellers et al. 2014). The waves and strong currents associated with tropical storms can cause increased breakage, so pre and post-post storm activities may also help to retain and recover material. When strong storms are forecasted, farmers could consider harvesting their crop before the storm. And then following the storm, they could survey the seafloor under and around their farms to recover any propagules that may have been dislodged. Ultimately, reducing breakage and loss of *K. alvarezii* is beneficial to farmers because the more biomass that they can bring to shore, the more they have available for sale (Ask et al. 2020).

In addition to minimizing breakage and collecting lost fragments, seaweed farmers could also consider heighted interception measures. Traditional line and raft methods used for cultivating seaweeds in the Caribbean allow for the free movement and loss of the seaweed propagules in the water column. During harvest and reseeding, when breakage is more likely to occur, farmers could experiment with deploying a temporary protective net to catch material that would otherwise be lost to the surrounding environment. At sites less than 3 or 4 meters deep, turbidity curtains that were originally developed to control silt and sediment during marine construction and dredging, could work as a sleek seaweed interception technology. More permanent modifications to the standard off-bottom farm array design may also be warranted.

Using tube nets, instead of made-loops and a longline, may result in less breakage and/or lost fragments. If tube nets prove expensive or difficult to source, perforated polyethene bags (like those used to package fruits and vegetables) could also be tried. Caution is expressed with the use of perforated polyethene bags. This could likely add to the existing problem of plastics in the ocean. Installing a secondary, permanent containment system around the entire farming array could also help to intercept large pieces of *K. alvarezii* that break off. For example, Castelar et al. (2009) used a nylon (60 mm mesh) to intercept material that fell off their floating rafts. The tradeoffs with this approach are that additional, large nets can provide entanglement hazards for marine animals like turtles, fish, and seabirds. If the nets are not replaced regularly, or if they are damaged, they can become a source of marine plastic pollution. Acquiring the netting also results in an additional cost on the part of the farmer. In some locations, like the tropical U.S. where aquaculture gear restrictions are stringent, the use of a secondary net may not be approved.

Vessels and farming gear can also be vectors that carry *K. alvarezii* from one location to another. Therefore, after working at a site where *K. alvarezii* is grown, farmers should check their boat(s) and equipment for fragments of *K. alvarezii*. Then the boat(s) and gear should be rinsed in fresh water, and when possible, left in the sun to air dry before being used at another location (Bruckerhoff et al., 2015).

Co-cultivation of *K. alvarezii* with consumers of macroalgae (ex: sea urchins or crabs) could also play a part in an increased containment strategy. There are five sea urchin genera commonly found in the Caribbean (*Diadema, Echinometra, Tripneustes, Eucidaris and Lytechinus*), and while they have all been shown to feed on macroalgae, *Diadema antillarum* has been shown to significantly reduce fleshy macroalgae (Williams 2022; Butler IV et al. 2024). The Caribbean King Crab (*Maguimithrax spinosissimus*) is also known to be a hearty consumer of seaweeds, and they have been successfully reared in mesh cages moored in backreef habitats (Adey, 1987; Coen 1988; Butler and Mojica 2012).

Thus, the crabs or urchins could be cultivated on the seafloor directly underneath and around the seaweed cultivation array and then dislodged seaweed biomass would be consumed by them, thereby reducing the potential for transport of *K. alvarezii* fragments away from the farming site. There are also additional economic benefits of this approach as the urchins and crabs could also be harvested and sold regionally or to international markets.

Resource managers electing a containment and maintenance strategy could also apply permitting tools to support containment and maintenance goals. They could issue permits that allow existing seaweed farmers cultivating *K. alvarezii* to continue their practices. Then, the issuing agency could apply a cap to the total number of farms or farmers allowed to work with *K. alvarezii*, and/or restrict the approval of permits for *K. alvarezii* to specific bays, islands, etc. It is worth noting, however, that to be effective this capped permitting strategy does require that a permitting system is established and enforced, and this necessitates financial and labor investment from the issuing agency. Lastly, as there is concern that the potential of *K. alvarezii* spread could be amplified if existing farms are abandoned (Sellers et al. 2014), it would be prudent for resource managers to require that all *K. alvarezii* be removed from a cultivation site when farming operations are paused seasonally and/or ceased entirely.

A containment management decision may be justified for *K. alvarezii* in the Caribbean if managers believe that the ecosystem and societal benefits of *K. alvarez*i farms outweigh the potential impacts. The decision may also be justified if managers determine that the tools available to them will be ineffective in reducing or eradiating *K. alvarezii* from the region (Hussner et al. 2017). A containment strategy could also be combined with other strategies (ex: increased monitoring, containment, and reduction) as part of a larger management program (Ibid.).

3) Reduction, nuisance control, and potential eradication

Reducing *K. alvarezii* populations, and thus the threat of an invasion, in Caribbean waters may be possible because no large infestations have occurred.

However, reducing *K. alvarezii* populations will require a coordinated effort between seaweed farmers and resource managers, and likely other supporting agencies.

For reduction strategies to be effective, buy-in would have to be obtained from seaweed farmers because they would need to cease farming *K. alvarezii* as it is a vector for *K. alvarezii* dispersal. An education campaign explaining the threats posed by its continued cultivation and proliferation of *K. alvarezii* would be necessary. In addition to focusing on the ecological threats, the campaign could also provide more information about the increased incidences of disease, extensive herbivory, and die-offs that have occurred on *K. alvarezii* farms in locations outside the Caribbean over the past 15 years[4]. The campaign can then encourage these producers to transition into growing a native seaweed species. Some candidate native Caribbean species include: *Eucheuma isiforme, Hypnea musciformis, Soliera filiformis, Agardiella rasmosissima,* or *Meristiella* spp. Each of these species produces carrageenan that is like that produced by *K. alvarezii*, so they may be acceptable substitutes for the existing regional seaweed applications like shakes and cosmetics. They may not be acceptable substitutes in the global carrageenan market, but this would need to be determined through additional characterization of the carrageenan produced by the cultivars and in a variety of environmental conditions.

Of all the candidate alternative species, *E. isiforme* is the most closely related species to *K. alvarezii*; in fact, until 1996 *K. alvarezii* was named *Eucheuma alvarezii* or *Eucheuma cottonii*, but molecular studies of the species' genotype led to its renaming (Guiry & Guiry 2020). Some farms in the Caribbean are already growing *E. isiforme*, and there is also a small amount of peer-reviewed and extension literature providing guidance on cultivation strategies for this species (Smith & Gustave 2001; Roberson et al. In Review, TNC Caribbean BMP). So, transitioning *K. alvarezii* farms to *E. isiforme* farms may be the most logical first step. The trade-off in doing so, is that *E. isiforme* does not grow as fast as *K. alvarezii.*

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[4]These issues are associated with the loss of vigor due to clonal propagation, in combination with physiochemical stress resulting from higher water temperatures and greater variations in salinity associated with climate change (Msuya 2011; Tano et al. 2015; Largo et al. 2020; Rusekwa et al. 2020).

Typically, growth rates of *E. isiforme* hover around 2% per day, although growth of 4 - 6% per day has been observed (Dawes 1974; Roberson, unpublished raw data). In contrast, *K. alvarezii* strains have been selected for maximal growth rates; they are commonly 5 - 9% per day, but they have been observed to be as high as 15% during the alga's period of fastest growth[5] (Montúfar-Romero et al. 2023). Thus, transitioning from farming *K. alvarezii* to *E. isiforme* may not immediately appeal to farmers as their yields for the same unit area and time will be reduced. More ocean area may be required to produce the same seaweed biomass. Given these limitations, the transition to cultivating native species could be greatly facilitated if government agencies or industry can offer capacity-building like government breeding programs to improve growth rates, training in cultivation practices, free or inexpensive source of seed, and potentially other subsidies. The verification of a clear and reliable market for these new species would also derisk the transition to new species for farmers.

Reducing or eradicating *K. alvarezii* from Caribbean waters will require a coordinated and wide-scale campaign. Prior to launching such an effort, evidence-based assessments of both risks and benefits should be completed by research groups independent from those proposing the eradication effort (Kopf et al. 2017). These assessments should consider the perceived risks and benefits of all stakeholders, include expert estimates that quantify the potential benefits and likelihood and severity of risks, and be conducted in a transparent fashion (Ibid.). The importance of a thorough assessment prior to implementing control measures cannot be overstated. Removing or eradicating naturalized species can have unintended ecological impacts that may need secondary mitigation, and sometimes these impacts may be unanticipated because during control, it becomes evident that the established performs functional roles in food webs, provides habitat, or other ecological roles to native species (Kopf et al. 2017). Perverse food web outcomes have been observed following control of other species (Zavaleta et al. 2001; Ballari et al. 2016).

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[5] Approximately 20 – 35 days after outplanting.

In the case of *K. alvarezii*, its removal may result in increased herbivory of other native algae, and in some locations, mean that algal biomass is not available to herbivores at the quantities that it was prior to control, which may impact their survival. Biophysical changes, like habitat loss or alteration, or reduced sediment stability and nutrient transfer, have also be observed following invasive macrophyte removal (Schlaepfer et al. 2011; Lampert et al. 2014). For these reasons, when experts were asked to rank possible management actions for controlling marine invasive species, they highly prioritized raising public awareness[6] and discouraging the commercial use of invasive species over biological control actions (Giakoumi et al. 2019).

If the results of the risk-benefit analysis for a region suggest that reduction and attempted eradication of *K. alvarezii* is the best path forward, resource managers have a suite of tools to choose from. As described above, they could begin by communicating with existing users of *K. alvarezii* to explain the threats posed by its continued cultivation and proliferation, prohibit *K. alvarezii* farming, and provide alternative species and support in a transition away from *K. alvarezii* farming. Then, they could launch hand-weeding efforts on reefs where *K. alvarezii* has become established (this would likely require scuba divers anywhere where the water is deeper than 1 m). To facilitate and motivate removal, they could legalize unlimited harvest of *K. alvarezii* from the wild. In areas with larger established populations of invasive aquatic macrophytes, a combination of hand-harvesting and targeted vacuuming has been shown to offer the best combination of fewest impacts on nearby species and effective removal (Hussner et al. 2017). Remotely operated underwater drones could also potentially be used to help identify and remove *K. alvarezii* individuals from reefs (Simberloff 2021). The tradeoff with manual removal is that it, in addition to the ongoing labor expenses, also misses the microscopic *K. alvarezii* lifestages that can create the equivalent of a persistent local seed bank.

[6] According to effectiveness, feasibility, acceptability, impacts on native communities, and cost.

There are also several, more experimental, approaches like the release of intentional biocontrols or gene silencing which have been used in other cases of aquatic species' invasions (Simberloff 2021). In Panama and Hawaii, native sea urchins have been proposed to be an effective biocontrol agent for *K. alvarezii* (Conklin and Smith 2005; Sellers et al. 2014). Gene-silencing using CRISPR-Cas9 technology has been used effectively for population control of other nuisance species (i.e. mosquitos; National Academies of Sciences 2016) and it could also be considered as a tool for a longer-term, combined control and reduction strategy for *K. alvarezii* populations in the Caribbean. Gene drives permit engineered genes to be spread throughout populations, even when a trait confers negative fitness or reproductive success. Using similar techniques, a sterile cultivar of *K. alvarezii* could be developed and farmed, and this would reduce the risks that farming it would lead to recruitment of individuals on coral reefs. Sterilization has been recommended by phycologists as a tool for both preventing invasiveness of non-native species and for preventing potential introgression of crop genetic material into wild populations when cultivating native species (Louriero et al. 2015). Applied chemical controls, although commonly applied to small, fresh waterbodies are not recommended for large-scale marine applications. However, initiatives to reduce anthropogenic nutrient inputs to coastal waters could potentially have a trickle-down effect on naturalized *K. alvarezii* populations. If the algae become nutrient limited their growth rate will drop and their spread and recruitment may too. Reduced nutrient inputs to the coast would also be beneficial for other coastal marine species. Due to their experimental nature, associated costs, and risks of unintended consequences we further emphasize the necessity for a thorough ecological risk assessment prior to implementing any of these experimental approaches. It must also be noted that reduction and potential eradication efforts require a long-term commitment; innumerable projects have substantially lowered populations of their target species initially, but then lost progress made because the cost of the project was unsustainable, or management interest waned (Hussner et al. 2017).

Summary of SWOT Analysis

In summary, the cultivation and management of naturalized *K. alvarezii* in the Caribbean is a complex topic that requires additional and timely attention and discussion. At this time no single policy and management approach is clearly superior to the rest. Rather, there are strengths, weaknesses, opportunities, and threats associated with *K. alvarezii* cultivation in the Caribbean (Table 1).

STRENGTHS	**WEAKNESSES**
• Already naturalized/established species in some parts of the Caribbean Sea (Belize, Venezuela, Costa Rica, St. Lucia, etc.) • Kappa-carrageenan, produced by *K. alvarezii*, is highly desirable in the global hydrocolloid market • Used locally and regionally in recipes for shakes and smoothies, as well as in formulations for body products • *K. alvarezii*, like all seaweeds, removes excess nutrients and carbon dioxide from ambient ocean water, which works to maintain good water quality in proximity of the farms. • *K. alvarezii* grows quickly. More biomass potentially results in higher revenue for farmers, more habitat for associated marine fauna, and greater contribution of ecosystem services • K. alvarezii is shown to be more susceptible to high water temperatures that other red seaweeds and this may restrict the extent of its establishment beyond seaweed farms that either operate seasonally and/or are sited in cooler waters	• Strains of *K. alvarezii* are invasive in some locations where it is farmed, whereas invasiveness is considered minimal in other geographies. • Currently no standard nursery process using sexual offspring to produce new seeds --> results in reduced genetic diversity of the crop over time • Shown to be more susceptible to high water temperatures than other Eucheumatoids. • Frequent incidence of disease in other regions where it is cultivated.
OPPORTUNITIES	**THREATS**
• Ready export market for *K. alvarezii* --> Estimates are that if a particular Caribbean region could produce 1,000 dry tons of *K. alvarezii* annually it would be able to participate in the global carrageenan trade. • Conduct farm-level molecular characterization of seaweeds currently in cultivation • Work with agency partners to develop early detection and containment program for *K. alvarezii* and other potentially invasive algal species • Conduct evidence-based assessments of the economic costs of potential control or eradication measures • Conduct evidence-based assessment of ecological risks and benefits of *K. alvarezii* control or eradication • Train farmers in best practices for biosecurity practices to minimize material loss from their farms and prevent possible spread of *K. alvarezii* to new parts of the coastline • Provide seed source and training for farmers to support transition to farming with native seaweed --> more ocean area may be required to produce same quantity of seaweed biomass	• Strain fatigue (potential loss of vigor due to clonal propagation and slow deviation away from desirable characteristics) • Water temperatures may exceed the tolerance range of *K. alvarezii* for part of the year, and likely that this period of unsuitably warm water will get longer • Potential to overgrow and smother coral reefs, which would result in seaweed-dominated, low-diversity reefs and changes to the bottom structure of the reef. Potential trickle-down impacts to dive tourism, spiny lobster, and queen conch. • Absence of policies or regulatory guidance around the cultivation of non-native algal species in the Caribbean

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