Opportunities and barriers to the expansion of seaweed aquaculture in Nova Scotia

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Executive summary

Seaweed aquaculture is a multi-billion-dollar global industry. In terms of wet weight, seaweeds are by far the largest single group of organisms cultured within the marine environment. Presently, the majority of cultured seaweed production occurs in Asia, but seaweed aquaculture is emerging in other parts of the world.

Seaweeds are incredibly flavourful and rich in nutrients. Consequently, direct human consumption is one the largest markets for seaweed products. The food processing industry is just as important and uses three seaweed extracts (i.e., agar, alginate, and carrageenan) as emulsifying and thickening agents. These extracts are also important components in pharmaceutical and biotechnology products. In addition, seaweeds are rapidly gaining commercial interest for their high yields of bioactives and nutraceuticals, which can be of benefit to human, plant, and animal health. However, processing seaweeds for these markets can be very costly in terms of time, energy, expertise, and equipment.

Seaweed aquaculture is widely considered to be environmentally benign and may generate more environmental benefits than it does negative impacts. For example, seaweed aquaculture could help mitigate eutrophication and generate habitat for a diversity of fish and invertebrates. There are also arguments that the large-scale expansion of seaweed aquaculture could help sequester carbon and buffer ocean acidification. However, these potential environmental benefits are poorly understood and there is currently little direct evidence to support these claims.

There is significant interest in developing and expanding the seaweed aquaculture industry in Nova Scotia. Presently, most proponents are interested in farming sugar kelp (*Saccharina latissima*) and potentially winged kelp (*Alaria esculenta*) and horsetail (*Laminaria digitata*). As there are already several sugar kelp operations and hatcheries in existence / development, there is strong potential for the immediate expansion of the sugar kelp industry in Nova Scotia. There are also several other species which have commercial potential, however, competition with wild harvests (e.g. *Palmaria palmata*) and with existing producers (e.g. *Chondrus crispus*), or the potential for negative environmental impacts (e.g. *Ulva* spp.), may pose barriers. Other than kelp, the culture of nori (*Pyropia* and *Porphyra* spp.) probably has the most potential for development, but further research is greatly needed into possible production methods, processing, and markets.

The biggest barriers to the expansion of seaweed aquaculture in Nova Scotia include; limited processing capabilities, unclear access to markets, and unknown consumer demand. In addition, many stakeholders have expressed their frustration with the existing regulatory process as the industry is subject to the same licencing, leasing, and monitoring guidelines as shellfish aquaculture, which many proponents feel are disproportionally stringent relative to its potential for generating negative environmental impacts. If government, industry, and scientists collaborate on these issues, the industry has strong potential to expand over the next several decades.

Aims and objectives

This report is aimed at prospective growers and regulators interested in seaweed aquaculture that have little or no background in the subject. It is designed to get any reader up-to-speed with: (1) which seaweed species may be the most suitable for aquaculture in Nova Scotia; (2) the potential production and processing methods that might be involved; (3) the possible target markets available; (4) the relevant regulatory and application processes; and (5) the potential opportunities and barriers facing this emerging industry. More emphasis is placed on open-water seaweed aquaculture, rather than land-based, as this type of production is typically associated with higher yields, lower costs, and potentially requires less advanced technologies and specialist expertise.

1. Introduction to seaweeds

1.1. What are seaweeds?

The term 'seaweed', or 'macroalgae', simply refers to algae that are large enough to be seen without a microscope. Like all plants, seaweeds need light for photosynthesis (see Section 1.4). However, they are only distantly related to flowering / vascular plants. Their anatomy, tissues, and life cycles are very different.

1.2. Seaweed anatomy

Unlike flowering / vascular plants, seaweeds do not have leaves, stems, and roots, and they do not produce seeds or fruits (reviewed in Mouritsen, 2013). Instead of using roots, seaweed cells absorb nutrients and gasses directly from the surrounding water. For some species, seaweed cells do not display any differentiation, meaning all their cells are virtually identical, and each cell is responsible for generating what it needs to survive. While other species have cells which are adapted to carry out specialised functions, such as transplanting salts and sugars within the organism (Pereira, 2021). Seaweeds with cell differentiation are generally comprised of three to four distinct structures (Figure 1):

1. **Holdfast:** A root-like structure that anchors the organism to the seafloor.
2. **Stipe:** Connects the holdfast to the rest of the organism.
3. **Blades:** These make up the bulk of the organism and are the primary tissues responsible for photosynthesis. In some cases, the blades have a distinct 'midrib' running through the centre of the blade. Scientists may use the term 'thallus' or 'thalli' to describe both the holdfast and blades combined, and the term 'meristem' for describing where the blades meet the stipe.
4. **Air-filled bladders:** Some species have specialised structures that allow the blades to float in water, maximising their access to sunlight.

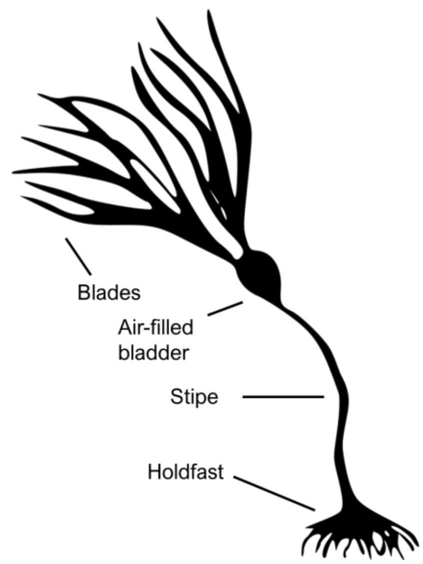

Figure 1 | Schematic diagram of a seaweed and its major structures.

1.3. Seaweed growth

Seaweeds commonly grow in one of three different ways (reviewed in Pereira, 2021):

1. **Diffuse growth:** Where new cells can form anywhere on the organism (e.g., *Ulva lactuca*, see Section 7.5).
2. **Apical / marginal growth:** Where new cells only form at the tips or outer areas of the blades. Thus, the oldest tissues are located at the base of the seaweed (e.g., *Chondrus crispus*, see Section 7.2)
3. **Meristem growth:** Where new cells only form at the meristem, causing the organism to lengthen as it grows. This means the oldest tissues are located at the tips of the seaweed. Consequently, the stipes may persist for multiple years, but the blades may breakdown and be replaced by new tissues every year. This

can help the seaweed reduce the number of epiphytes[1] growing on its outer surface. All species of kelp (see Section 7.1) display this form of growth.

1.4. Photosynthesis and respiration

Seaweeds photosynthesize during the day, a process which converts sunlight into glucose and other carbohydrates (reviewed in Mouritsen, 2013). This chemical reaction occurs within the cells and requires carbon dioxide (CO_2) which is absorbed from the surrounding water. It also requires phosphorous, nitrogen, and a variety of other nutrients and minerals to work effectively. Oxygen is released into the water as a by-product.

Photosynthesis stops at night when respiration becomes the dominant chemical process. Respiration absorbs oxygen from the water, and uses the glucose created from photosynthesis, to create energy necessary for seaweed growth and repair. CO_2 is released into the water as a by-product. As seaweeds typically photosynthesize more than they respire, both of these processes usually result in a net removal of CO_2 from the surrounding seawater and a net gain in oxygen (also see Section 6.1.3).

1.5. Functional groups: green, red, and brown seaweeds

Seaweeds can be divided into three basic functional groups based on the colour of their primary pigments; green, red, and brown. These pigments are responsible for absorbing light and / or protecting tissues from ultraviolet (UV) radiation, and can be separated into chlorophylls, carotenoids, and phycobilins (Table 1).

There are an estimated 10,000 species of seaweed in the world (reviewed in Mouritsen, 2013). Of these, 6,200 species (or 62 %) are presumed to belong to red seaweeds, while the remaining 3,800 species are thought to be evenly divided between brown (19 %) and green (19 %) seaweeds (Mouritsen, 2013). All species of kelp (see Section 7.1) are brown seaweeds. Green seaweeds contain the same pigments as vascular plants (i.e., chlorophylls and carotenoids), while red and brown seaweeds contain different pigments. Red seaweeds are unique in that they contain phycobilins (Pereira, 2021). These pigments are especially efficient at absorbing wavelengths that are not well absorbed by chlorophyll-*a* (i.e., red, orange, yellow, and green light).

1.6. Life history

Seaweed life histories can be incredibly complex. In fact, many species exhibit multiple life stages that are so distinct from one another, that they can be easily mistaken for an entirely different organism (also see Section 2.1). Generally, their life stages alternate between microscopic phases naked to the eye, and large, conspicuous phases (i.e., the large, edible, plant-like structures we identify as 'seaweeds'). These different life stages may employ sexual and asexual reproduction and alternate between being diploid and haploid [2].

Asexual reproduction may occur through the release of spores, which can either be mobile (e.g., 'zoospores', which use flagella to propel themselves through water) or immobile (e.g., 'aplanospores' which passively float in the water column). Asexual reproduction may also occur through 'fragmentation', where 'propagules' (i.e., small clusters of cells) or small pieces of tissue are shed / released from the blades. In all cases, these tissues and cells can then disperse and develop into completely independent organisms (reviewed in Pereira, 2021). In contrast, sexual

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[1] 'Epiphytes' are organisms that grow on other organisms. On seaweeds, this may include bryozoans, hydroids, and even other seaweeds, which can negatively impact seaweed photosynthesis and their physical appearance / product quality.

[2] 'Diploid' refers to cells which contain two complete sets of chromosomes, with each parent contributing a chromosome to each pair. In contrast, 'haploid' refers to cells which contain a single set of chromosomes. Most cells designed for sexual reproduction are haploid (e.g., sperm, eggs, and other gametes).

reproduction typically involves the release of male and female gametes (e.g., sperm and eggs). To increase the probability of gametes encountering and fusing with one another, sperm may be equipped with light sensitive eyespots and flagella. Furthermore, some species may release pheromones to attract sperm, and secrete a thick slime to ensure the egg and sperm cells stick together (reviewed in Mouritsen, 2013).

Table 1 | Classification and pigment composition of seaweeds. Adapted from Pereira (2021).

Group	Phylum	Chlorophylls	Carotenoids	Phycobilins
Greens	Chlorophyta	*a, b*	β-carotene, lutein, neoxanthin, violaxanthin, and zeaxanthin	
Reds	Rhodophyta	*a, d*	β-carotene, lutein, and zeaxanthin	R-phycocyanin mostly, but also R-phycoerythrin
Browns	Ochrophyta	*a, c*	β-carotene, fucoxanthin, and violaxanthin	

1.7. Latin names vs. product names

Some companies market seaweed-based products in an ambiguous manner which could lead to confusion over the exact species being sold. For example, 'Atlantic kombu' and 'Atlantic wakame' may refer to multiple species, all of which are scientifically unrelated to traditional kombu and wakame from Asia (see Section 2.2). In addition, many species have multiple common names, some of which may not be unique to one species. For example, 'winged kelp' may refer to several species including *Alaria esculenta* and *Alaria marginata*. Therefore, to avoid confusion, Latin names are used throughout this report, and are shortened to better reflect the names used by regulators, growers, and scientists operating in Nova Scotia:

- ***Alaria*** refers to *Alaria esculenta*, commonly known as winged kelp, dabberlocks, and badderlocks.
- ***Ascophyllum*** refers to *Ascophyllum nodosum*, commonly known as rockweed, Norwegian kelp, knotted kelp, knotted wrack, and egg wrack.
- ***Chondrus*** refers to *Chondrus crispus*, commonly known as Irish moss and carrageen moss.
- ***Laminaria*** refers to *Laminaria digitata*, commonly known as horsetail and oarweed.
- **Nori** refers to *Pyropia* and *Porphyra* spp.
- ***Palmaria*** refers to *Palmaria palmata,* commonly known as dulse, dillisk, dilsk, red dulse, sea lettuce flakes, and creathnach.
- ***Saccharina*** refers to *Saccharina latissimi*, commonly known as sugar kelp, sea belt, devil's apron, and lasagna kelp.
- ***Ulva*** refers to *Ulva* spp., commonly known as sea lettuce.

2. History of seaweed aquaculture

Seaweed aquaculture has a long history. For example, the ancient Hawaiians (prior to 1810) cultivated a wide variety of seaweed species (known collectively as 'limu') within coastal ponds (reviewed in Kim et al., 2019). Historical evidence suggests that undesirable seaweeds were actively removed, and that more desirable species were transplanted from one island to another (Figure 2A). However, as detailed in the following sections, the most important industrial developments in seaweed aquaculture occurred in Asia during the last 400 years.

2.1. Nori / laver (*Porphyra* and *Pyropia* spp.)

Perhaps some of the most familiar edible seaweeds are red seaweeds[3] of the genera *Porphyra* and *Pyropia*. In Asia, these species are collectively known as 'nori' (Figure 2B) and are used worldwide for wrapping up sushi rolls, and as ingredients in soups and salads. In contrast, some European countries commonly refer to these seaweeds as 'laver', and provide the key ingredient for 'laverbread', a traditional British and Irish cuisine that is usually spread on toast (Figures 2C).

The first steps towards nori cultivation took place in Japan between the 16th – 18th centuries (reviewed in Delaney et al., 2016). During this time, fishermen started planting racks of bamboo branches in shallow coastal waters to encourage the settlement, attachment, and growth of wild nori spores (The Seaweed Site, 2021). As technology progressed, bamboo branches were replaced with nets horizontally suspended in the water between bamboo posts (Figure 2D). As the nori aquaculture industry relied on wild spores, production yields varied greatly from year to year. However, in the 1940's, the industry almost collapsed entirely. Yields hit a record low and wild nori had essentially disappeared from Japanese coasts (Smithsonian, 2021). As this was at the end of World War II, Japan was already struggling with a multitude of issues, including a national food crisis. Consequently, the decline of nori had a dramatically negative effect on the country.

At the same time, a young female scientist, named Kathleen Drew-Baker, was investigating the life cycle of a very closely related seaweed (*Porphyra umbibicalis*, or 'laver') on the coast of Wales, some 9000 km from Japan. Drew-Baker had recently married and subsequently been fired from the University of Manchester, which did not permit its female lecturers to marry. Nonetheless, Drew-Baker continued her (now unpaid) research and went on to discover that *P. umbibicalis* has a formerly hidden life stage which appears as a pink, slimy, filamentous algae that bores into oyster shells (also see Section 7.4). She also discovered that this life stage releases spores which then grow into the large and edible form of the seaweed (Smithsonian, 2021). She published her findings in 1949 in the journal *Nature* (Drew, 1949).

Aided by this new knowledge, Japanese scientists helped growers collect wild nori spores using oyster shells. They also developed a land-based system for culturing the spores in temperature-controlled tanks, which could then be reintroduced into the sea to complete their development (Delaney, 1993; Inglis-Arkell, 2017; Shetterly, 2018). Another major innovation then occurred in the mid-1960's, when growers began freezing nets germinated with nori seedlings (reviewed in Hafting et al., 2015). The seedlings could then be introduced back to the sea once growing conditions were optimal (for more information on nori culture, see Section 7.4). The ability to control the timing of nori growth greatly stabilized Japanese nori production and extended the length of the growing season. In addition, the freezing process reduced disease and epiphyte growth, which improved the overall quality of the product. Over time, Japanese growers also began selecting species and strains that were faster growing and more suited to their local environmental conditions. Innovations were also made in nori processing. For centuries, nori

[3] Red and brown seaweeds usually turn green during cooking as chlorophyll is green in colour and is more resistant to degradation than other seaweed pigments.

was eaten fresh, either whole or as a paste. However, technology from Japan's paper industry was adapted to shred the nori before pressing it into thin sheets for drying (Figure 2F), which greatly lengthened its shelf-life.

Thanks to all these developments, Japanese nori production increased 9-fold between 1949 and 1973 (reviewed in Hafting et al., 2015). In memory of her scientific contribution, Drew-Baker is still known as "the mother of the sea" in some parts of Japan, and a monument to her sits in the town of Uto (Figure 2E).

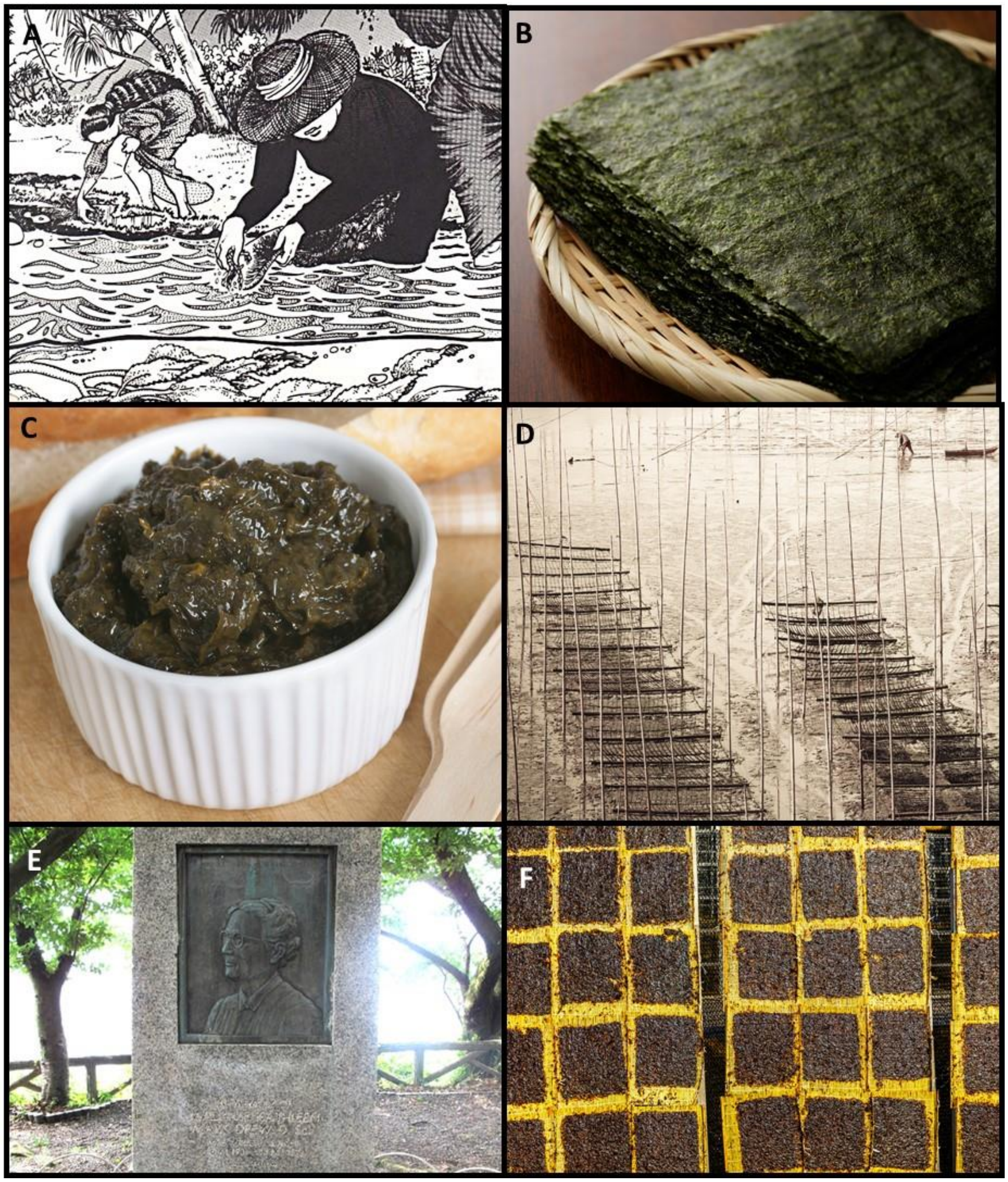

Figure 2 | (A) Print of native Hawaiians harvesting limu (State of Hawaii, Department of Education); (B) Dried sheets of nori, commonly used as a sushi wrapper (Shutterstock.com / K321); (C) Welsh laverbread made from *Poryphyra* red seaweed that has been cooked and pureed (Shutterstock.com / D. Pimborough); (D) A traditional Japanese seaweed farm using bamboo posts to suspend seeded nets (Shutterstock.com / Chuyuss); (E) A monument dedicated to Katherine Drew-Baker in Uto, Japan (Harris et al., 2013); (F) Nori is most commonly cooked, minced, pressed into thin sheets, and dried before retail. (Shutterstock.com / Stock for You).

2.2. Wakame and kombu

The kelp, *Undaria pinnatifida*, is more commonly known as 'wakame' in Asia, and is used in salads, stews, and soups (Figure 3A). Its cultivation began during the early 1940's in China and was quickly adopted by Japan and South Korea (reviewed in FAO, 2014; Hafting et al., 2015). A two-step cultivation process was then developed in 1955, which involved using land-based hatcheries to seed synthetic yarn (also see Section 7.1.3) with wakame spores. The 'seed string' was then transported to sea and unravelled around a series of suspended longlines. Similar advancements made during the 1960's for the culture of another kelp, *Saccharina japonica*, better known as 'kombu', which is a key ingredient in Asian soup stocks (Figure 3B). Before being retailed as food, both wakame and kombu are usually cooked, salted, pressed, and dried before being sold to and rehydrated by the consumer.

Figure 3 | (A) Wakame is usually sold pre-cooked and dried and can be used as an ingredient in salads and soups (Shutterstock.com / Ingrid Balabanova); (B) Kombu is also sold dried and is commonly used to provide a deep umami flavour to soup stocks (Shutterstock.com / JC08).

3. The global scale of open-water seaweed aquaculture

For many people, the word "aquaculture" is synonymous to finfish and shellfish farming. However, in terms of wet weight, seaweeds are by far the largest single group of organisms cultured within the marine environment (Figure 4). In 2019, around 60 % of all marine aquaculture production was comprised of seaweeds, followed by shellfish (30 %) and finfish (10 %). However, due to their comparatively low value, seaweeds only represented around 19 % of all marine aquaculture value, with finfish and shellfish representing 41 % and 40 %, respectively (FAO, 2021). Nonetheless, seaweed aquaculture is a highly lucrative industry, with annual global production levels worth an estimated USD $14.7 billion (FAO, 2021).

The seaweed aquaculture industry has displayed remarkably rapid rates of growth over the last 70 years (Figure 5). Prior to 1950, aquaculture contributed similar yields of seaweed to wild harvests (Lotze et al., 2019). However, between 1950 – 2019, aquaculture production increased from around 34,000 metric tonnes to 34.5 million tonnes, an increase of 10,000 % (FAO, 2021). In contrast, the quantity of seaweed harvested from wild populations has only doubled since 1950. Consequently, over 97 % of all the seaweed harvested around the world now derives from aquaculture.

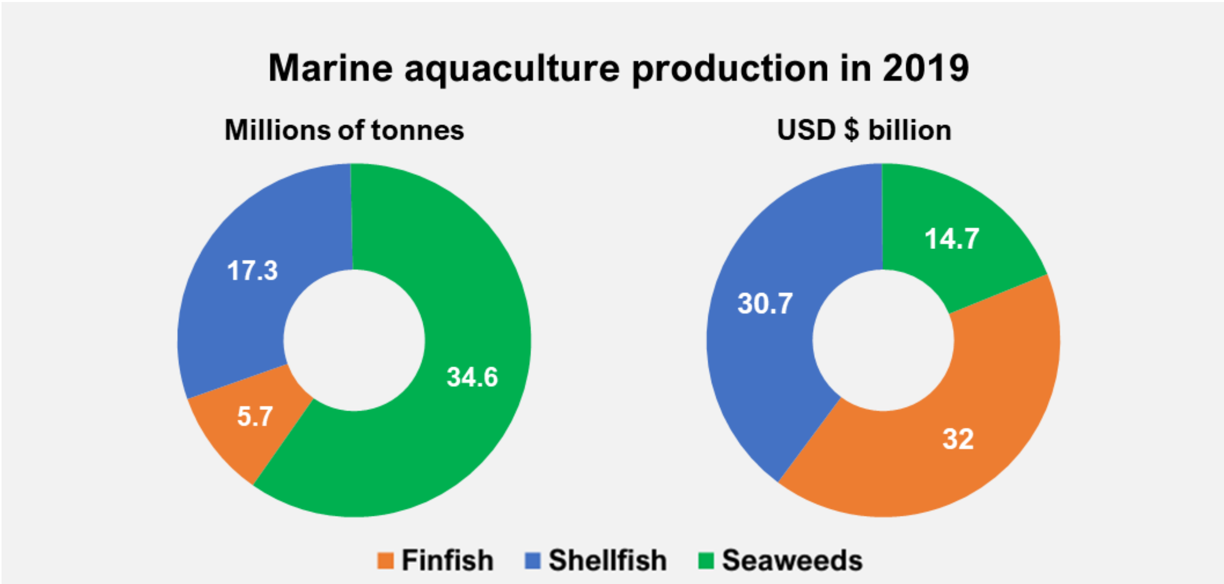

Figure 4 | Global quantity and value of marine aquaculture production in 2019 for finfish, shellfish, and seaweeds. Data from FAO (2021).

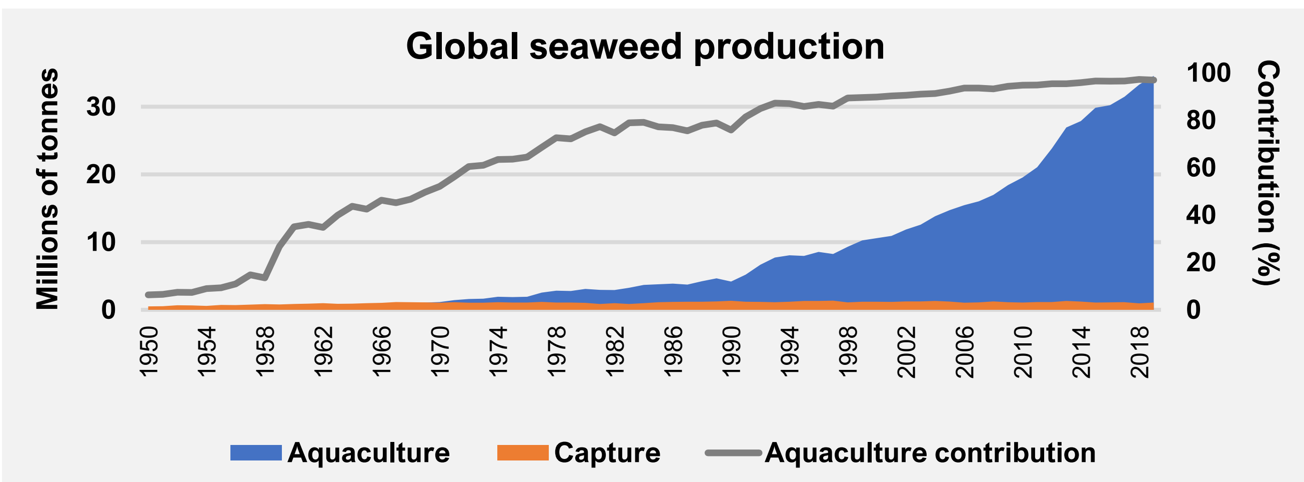

Figure 5 | Global quantity of wild and cultured seaweeds harvested since 1950. The line indicates the percentage contribution that aquaculture makes towards global seaweed production. Data from FAO (2021).

3.1. Seaweed aquaculture by country and functional group

Seven countries are responsible for nearly 99 % of all the cultured seaweed produced in the world (Figure 6). These are (in order of quantity produced): China, Indonesia, South Korea, Philippines, North Korea, Japan, and Malaysia. The fact that all these countries are within Asia may explain why the scale of this large and lucrative industry is often underappreciated in North America and Europe (Chopin, 2015; Clements and Chopin, 2016).

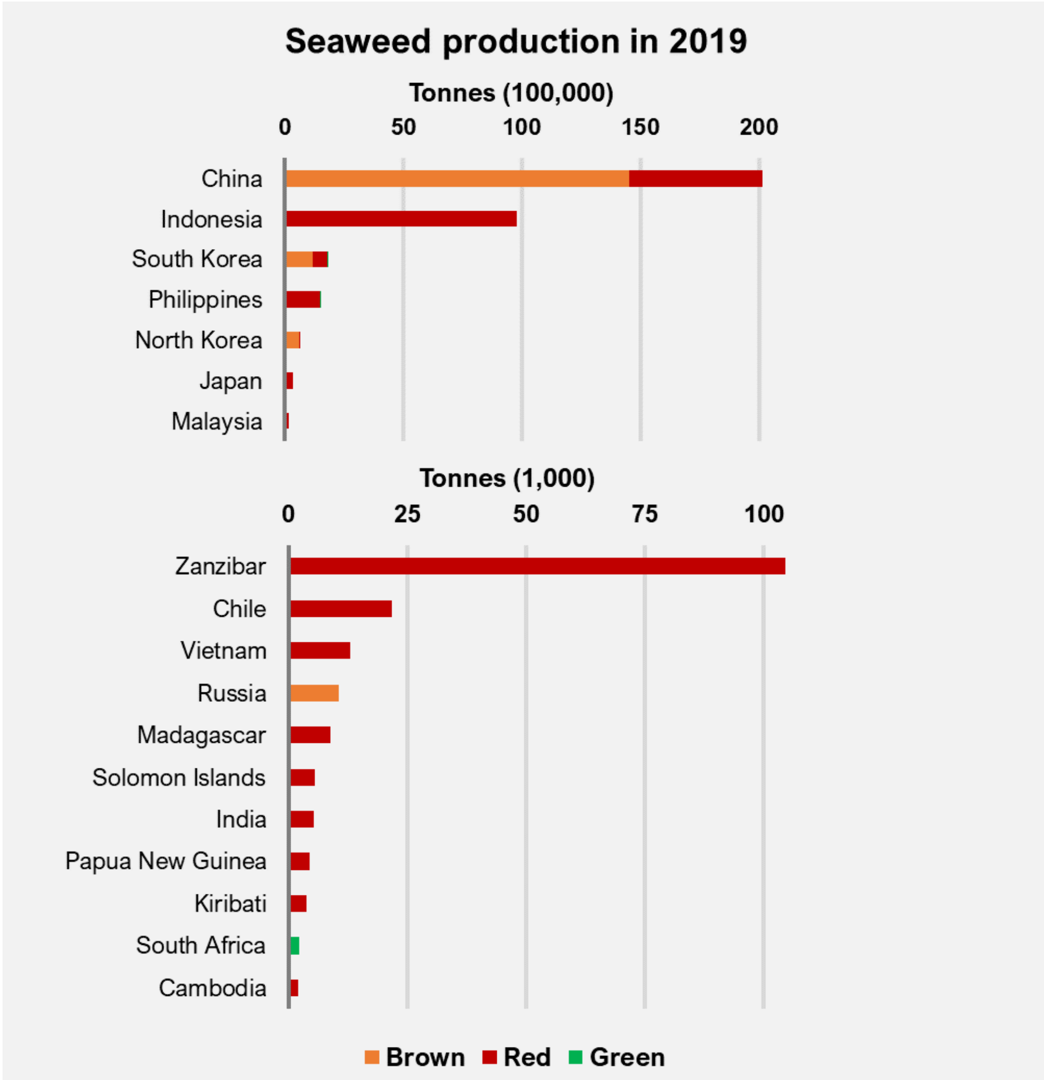

Figure 6 | The quantity of brown, red, and green seaweeds produced by aquaculture in 2019 for the top 18 producer countries. Data from FAO (2021).

Historically, brown seaweeds[4] have been the largest focus of the global seaweed aquaculture industry. However, the production of red seaweeds[5] has rapidly increased since the early 2000's and surpassed the production of brown seaweeds in 2013 (Figure 7). This shift is largely attributed to the rising demand for carrageenan, a commercially valuable chemical compound found in red seaweeds which is widely used in the food processing industry (see Section 5.2.2). Presently, 52 % of all seaweed production is comprised of red seaweeds and 48 % by brown seaweeds. Green seaweeds represent less than 0.01 % of all seaweed production and their production levels have remained relatively static for the past 40 years.

[4] Particularly, Kombu (*Saccharina japonica*) and wakame (*Undaria pinnatifida*) (Chopin and Tacon, 2020).
[5] Particularly, species within the genera *Euchema*, *Gracilaria*, *Poryphyra*, and *Kappaphycus*.

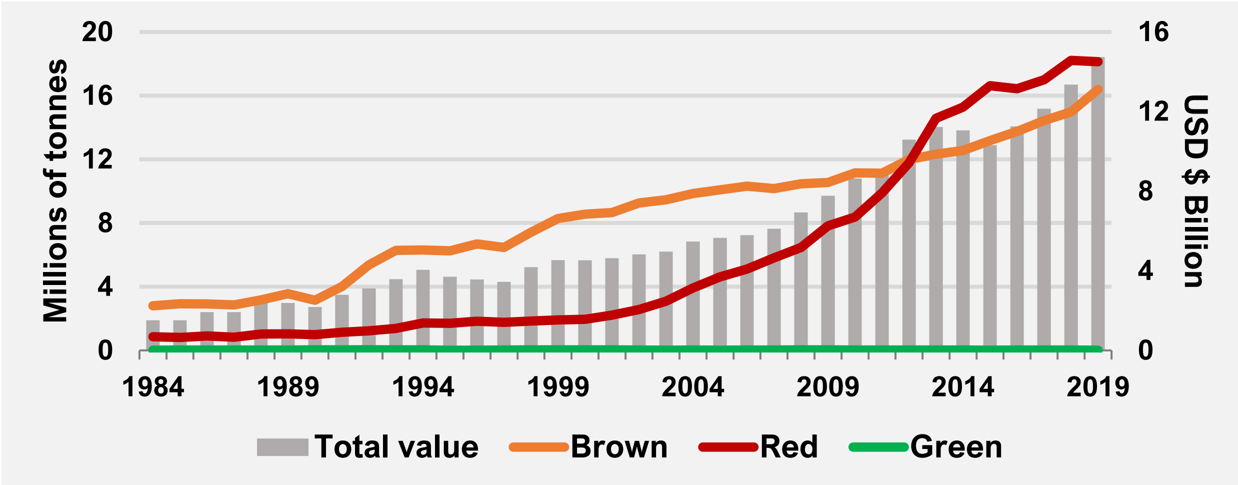

Figure 7 | Global quantity and value of seaweed aquaculture per functional group. Data from FAO (2021).

4. Seaweed aquaculture in Canada and Eastern USA

Seaweed aquaculture is a relatively new and small industry in North America. As a result, wild harvests are responsible for most seaweed production in Canada[6]. Correspondingly, there are multiple companies which harvest and process wild seaweeds, including in British Columbia (e.g., Canadian Kelp), Prince Edward Island (e.g., North Atlantic Organics), and New Brunswick (e.g., Atlantic Mariculture). In Nova Scotia, Tidal Organics, operated by Scotia Garden Seafood Inc, hold approximately 25 % of all wild rockweed (*Ascophyllum nodosum*) harvest leases within the province. This company dries and grounds *Ascophyllum* into powders for bulk retail to the agricultural and aquafeeds industries (Steve Owen, NRC, *pers. comms*, September 2022; also see Section 5.5). Nonetheless, there are several companies that culture seaweeds in Canada, as detailed in the following sections.

4.1. British Columbia

In British Columbia, Cascadia Seaweed culture sugar kelp (*Saccharina latissima*), *Alaria marginata*, sieve kelp (*Neoagarum fimbriatum*), and ribbon / Pacific dulse (*Develarea mollis*) on their five seaweed farms (total area = 20 hectares) on the east coast of Vancouver Island. The company was founded in 2019 and made their first commercial-scale harvest in 2021. Cascadia Seaweed's products are aimed at the agricultural feeds market and for human consumption under their brand, Kove Ocean Foods. There are also several other companies currently trialling the co-culture of shellfish and seaweed across the province. In addition, the Pacific Seaweed Industry Association is a non-profit, member-driven, industry association that works to develop awareness around the benefits and uses for seaweed, new technologies and innovation, and advocates for the industry.

4.2. Quebec

Three companies are actively involved in seaweed aquaculture in Quebec and grow *Saccharina*, winged kelp (*Alaria esculenta*), and dulse (*Palmaria palmata*). One company is a land-based hatchery which produces seeded lines. The other two are shellfish farms which also produce some seaweed on their leases. The latter two mostly aim their products for human consumption. In addition, two companies (Seabiosis and Salaweg) process wild and cultivated seaweeds into value-added products such as pesto, seasonings, relishes, and packaged salads. Finally, two more

[6] Data on seaweed production levels and value are rarely publicly reported due to confidentiality purposes.

Quebec-based companies are expected to begin seaweed farming by 2023, and several more are considering expanding into seaweed aquaculture in the next few years (Eric Tamigneaux, Merinov, *pers. comms*, October 2021).

4.3. New Brunswick

In New Brunswick, Fisheries and Oceans Canada (DFO) and the University of New Brunswick (UNB) have trialled the experimental co-culture of *Saccharina* and blue mussels (*Mytilus edulis*) on commercial Atlantic salmon (*Salmo salar*) farms (Reid et al., 2007). One grower, in collaboration with Dr Thierry Chopin from UNB, went on to establish Magellan Aqua Farms, which grows *Saccharina* and *Alaria* in the Bay of Fundy.

4.4. Maine

In Maine, the production of cultured *Saccharina* increased from an estimated 6.6 to 450 mt between 2015 – 2021 (St. Gelais et al., 2022). This increase of 3,000 – 6,700 % was largely due to the efforts of a single company. Atlantic Seafarms are the largest producer of cultured seaweed in USA. Their business model is unique in that they assist commercial fishermen in Maine in establishing *Saccharina* farms. The fishermen manage the farms using their own equipment and boats, while the company provides seeded lines and a guaranteed price per unit weight for the kelp once the crop reaches maturity. Atlantic Seafarms then process the kelp and market it for human consumption (Aurora Burgess, Atlantic Sea Farms, *pers. comms*, October 2022). Presently, 30 fishermen are involved in the initiative and the company acquires more than 400 tonnes of kelp each year (Sebastian Belle, Maine Aquaculture Association, pers. comms, 2022).

In addition, the Maine Seaweed Exchange offers training for prospective seaweed growers, and helps them to navigate regulation and organic certification, as well as sourcing growers with seeded lines, and providing advocacy and public education. While their 'Kelp Collaborative' program aims to create a network of organically certified seaweed farms, drying facilities, and processors to promote community-based industry expansion.

4.5. Nova Scotia

4.5.1. Acadian Seaplants Ltd.

Acadian Seaplants Ltd. are one of the largest and most successful seaweed producers in Canada. They are, however, unusual as they culture their own strains of Irish moss (*Chondrus crispus*) in a highly specialised land-based facility (the world's largest) on the South Shore of Nova Scotia[7] (see Section 7.2.3). They can also engineer the colour and texture of the seaweed. The result is a unique, high-quality product, completely free of epiphytes. The company is also the largest lease holder for wild *Ascophyllum* in Nova Scotia, and the largest harvester of wild *Ascophyllum* in the world, encompassing harvesting and processing operations in Canada, USA, Ireland, and Scotland. Acadian Seaplants market their products to the cosmetics, health, agricultural, and fertilizer industries, as well as the Asian seafood market. They are also in the process of trialling the value-added processing of cultured *Saccharina* grown in Nova Scotia (see Section 7.1.6).

4.5.2. Current scale of seaweed aquaculture in Nova Scotia

In Nova Scotia, 10 marine sites (total area = 342 hectares) are currently licensed for seaweed aquaculture, in addition to shellfish and other species. This number will likely increase as two license holders recently submitted applications to the Nova Scotia Department of Fisheries and Aquaculture (NSDFA) to add marine plants to their existing licenses, and four applications have been submitted for the development of small-scale land-based

[7] The National Research Council Canada (NRC) facility in Sandy Cove, Nova Scotia, also grows small quantities of *Chondrus* in their land-based experimental facility, which originally came from Basin Head, PEI.

hatchery facilities (Danielle St. Louis, NSDFA, pers. comms, August 2022). The open-water seaweed aquaculture industry in Nova Scotia is primarily aimed at culturing *Saccharina*, however, many growers are licensed to grow other species including *Alaria*, horsetail / oarweed (*Laminaria digitata*), sea lettuce (*Ulva* spp.), *Palmaria*, and species of *Pyropia* and *Poryphyra*. Presently, no growers are culturing and harvesting seaweeds on a full commercial scale. However, several organizations are currently trialling open-water *Saccharina* aquaculture, and some companies are capable of producing seeded lines (see Section 7.1.5 and Section 7.1.6).

4.5.3. Lobster Bay Aquaculture Development Area

There are several initiatives currently underway to facilitate growth of the Nova Scotia aquaculture industry, including the proposed Aquaculture Development Area (ADA) in Lobster Bay, Yarmouth County. The ADA will focus on the culture of shellfish and marine plants and is currently under assessment by NSDFA and the Municipality of the District of Argyle. The ADA will facilitate the lease application process (see Section 8) by pre-identifying areas that have already undergone extensive public consultation and biophysical data collection / analysis, to ensure identified culture sites maintain social, environmental, and economical suitability. Several companies have already expressed interest in establishing seaweed farms within the prospective ADA (Charlene LeBlanc, Argyle Municipality, *pers. comms*, May 2022).

4.5.4. Potential for industry expansion in Nova Scotia

Nova Scotia's 7,500 km long coastline stretches across the Gulf of Maine, Scotian Shelf, and the Gulf of St Lawrence. As a result, the province encompasses a very wide variety of oceanographic and climatic conditions which are likely suitable for the culture of many seaweed species (reviewed in Bradford et al., 2020). Furthermore, *Saccharina* has already been successfully cultured in the Bay of Fundy (see Section 4.3) and Cape Breton (see Sections 7.1.5) and several other species also have potential to be commercially cultured in the province (see Sections 7.2 to 7.6). Additionally, studies predict that several species of seaweed will undergo major distribution shifts and range retractions in Nova Scotia, in response to ongoing ocean warming (e.g. Khan et al., 2018; Wilson et al., 2019). Thus, harvests of wild seaweeds may become increasingly unpredictable. By allowing control over the growing season, depth and location, seaweed aquaculture could add an element of control, quality consistency, and predictability for seaweed harvesters in Nova Scotia. Lastly, there are a wide variety of stakeholders that are keen to develop the seaweed aquaculture industry in Nova Scotia (see Section 7.6). For these reasons, the Nova Scotian seaweed aquaculture industry has considerable scope for expansion.

5. Markets and commercial applications

As described in Section 2, seaweed consumption has a long history in many countries, often dating back for several centuries or more. Traditional uses for seaweed include food, fertilizer, animal feed, building materials, and for the production of glass, soap, and medicine (reviewed in Delaney et al., 2016). This section, however, generally focuses on more contemporary markets and commercial applications for seaweed.

5.1. Direct consumption

Approximately 40 % of all global seaweed production is directly consumed by humans in foods such as salads, soups, sushi, pesto, smoothies, seasonings, and a variety of snacks (World Bank, 2016). Typically, the processing of seaweeds for human consumption involves grading (i.e., sorting seaweeds by colour, thickness, and other measures of quality), cleaning, cooking, cutting, drying, and packaging. Often, these equipment and methods can be applied to more than one species. Perhaps one of the most familiar seaweed products in in Atlantic Canadian grocery stores is Fundy Dulse, which are dried pieces of wild harvested *Palmaria* (Figure 8). The company also sell a variety of other products including 'dulse soap', 'dulse powder', 'roasted nori' snacks, and 'flaked nori', 'kombu', and 'sea lettuce'. The powders and flakes are intended for use as ingredients in cooking and smoothies.

Figure 8 |Fundy Dulse is a familiar sight on grocery store shelves in Nova Scotia. Source: Noggins Corner Farm Market.

5.1.1. Nutritional content

Seaweeds can be very high in minerals (e.g., calcium, iron, and magnesium), trace elements (e.g., zinc, manganese, and selenium), vitamins (e.g., A, B, C, E, and K), fibre, vital oils, fats (including omega-3), and can be a source of protein and carbohydrates (Table 2). Consequently, seaweeds often contain many nutrients that are scarce in other foods. For example, the overall mineral content of seaweeds is typically 10 times higher than other fruits and vegetables (reviewed in Mouritsen, 2013; World Bank, 2016; Shannon and Abu-Ghannam, 2019). Specifically, *Palmaria palmata* can provide 50 – 80 mg of iron per 100 g dry weight compared to only 1.2 – 3.1 mg in the same quantity of lean beef, while 8 g dry weight of *Ulva lactuca* can provide 37 % of recommended Reference Nutrient Intake (RNI) of calcium per day compared to just 5 % RNI for the same quantity of cheddar cheese (Shannon and Abu-Ghannam, 2019). As a result, seaweeds are widely considered to be a healthy and highly nutritious food (reviewed in Mouritsen, 2013; World Bank, 2016; Shannon and Abu-Ghannam, 2019). However, their nutritional composition varies greatly between species as some seaweeds contain over 100 times more minerals or vitamins than others (Table 2). Nutrient composition also varies greatly within species, particularly between seasons, locations, and environmental conditions (reviewed in Holdt and Kraan, 2011).

5.1.2. Potential benefits and risks to human health

As detailed above, seaweeds are rich in nutrients, vitamins, minerals, and a wide variety of other compounds. Many of these compounds may be beneficial to human health. For example, some have potential as anti-cancers, anti-cholesterols, anti-diabetics, anti-hypertensions, anti-inflammatories, anti-obesities, anti-virals, antioxidants, and prebiotics. Collectively known as 'bioactives' or 'nutraceuticals', these seaweed-derived compounds are the focus of extensive and ongoing research investigating their ease of extraction, concentration in different species, and their effects on human health[8]. For comprehensive reviews on this topic, see Holdt and Kraan (2011), Cherry et al. (2019b) , Shannon and Abu-Ghannam (2019).

[8] All of these properties can also potentially benefit livestock and crop farming (see Section 5.5).

Table 2 | Nutrient composition of some seaweeds. Blank cells = unknown. Adapted from Holdt and Kraan (2011), Pereira (2011), Morais et al. (2020).

	Common name	Winged Kelp	Irish moss	Sea moss	Oarweed	Dulse	Nori / laver	Sugar kelp	Sea lettuce
	Species	*Alaria esculenta*	*Chondrus crispus*	*Gracilaria spp.*	*Laminaria digitata*	*Palmaria palmata*	*Porphyra spp.*	*Saccharina latissima*	*Ulva spp.*
% Wet weight	Moisture	73 - 86	72 - 78	85	73 - 94	84	77 - 91	73 - 94	78 - 80
Nutrient composition (% dry weight)	Protein	9 - 20	11 - 21	6.9 - 13.7	8 - 15	10 - 25	29 - 47	6 - 26	10 - 25
	Dietary fiber	33 - 42.86	10 - 34	24.7	37	29 -46	8 - 35	30 - 34.78	29 - 55
	Carbohydrate	38 - 59	55 - 68	66.1	48	46 - 56	43 - 44.3	52 - 61	36 - 43
	Lipid	1 - 2	1 - 3	1.3 - 3.3	1	0.7 - 3	0.3 - 1.7	0.5 - 1.1	0.6 - 1.6
Mineral composition (mg / 100 g dry weight)	Sodium	0	1200 – 4270	5465	3818	1600 – 2500	940 - 3627	2620	340
	Potassium	0	1350 – 3184	3417	11.5 - 79	7000 – 9000	2030 - 3500	4330	245
	Phosphorous	230	135			235	235	165	50 - 140
	Calcium	800	420 – 1120	402	1005	560 – 1200	330 - 440	810	350 - 840
	Magnesium	870	600 – 732	565	659	170 – 610	370 - 650	715	2600
	Iron	8.7	4 - 17	3.6 - 5	3.2 - 9	50 – 80	11 - 23		21 - 66
	Zinc	4.9	7.14	4.35	1.77	2.86	2 - 10		0.8
	Manganese	0.56	1.32		0.5	1.14	2 - 3		1.1
	Copper	0.24	0.5		0.1 - 5	0.3 - 76	0.63 - 7		0.49
	Iodine	22	24.5		14.5	10 - 100	1.7 - 17.3	15.9	1.6
Vitamins (mg / 100 g dry weight, * expressed as ppm)	A	0			-	1.59	3.65	0.04	0.017
	B1	0			1.25	0.07 - 1.56	0.14	0.05	0.02
	B2	0.3 - 1*			0.14	0.51 - 1.91	0.36	0.21	0.53
	B3	5*			61.2	1.89			100
	B5	0			0	0			
	B6	0.1 *			6.41	8.99			
	B8	0			6.4 - 35.5	0.0025			
	B12	0	0.6 - 4*		0.0005	0.01	0.03	0.0003	78.8
	C	100 - 500*	10 - 13*	16 - 149*	35.5	6.34 - 34.5	4.21	0.35	0.24
	E	0			3.43	2.2 - 13.9	0	1.6	
	Fatty acid	0			0	0.267	0.36	0	

Conversely, seaweeds can be high in salt, iodine, heavy metals (e.g., arsenic and mercury), bacteria, and other contaminants which have potential for health risks, toxicity, and bioaccumulation effects (for a comprehensive review, see Cherry et al., 2019a; FAO & WHO, 2021). However, contaminant concentrations in seaweeds varies greatly between species, the environmental conditions in which they are grown (e.g., temperature and degree of water pollution), and how they are harvested and processed. Overall, more research is required to better understand the risks and benefits of seaweed consumption, and into possible monitoring strategies and food safety regulations (FAO & WHO, 2021).

5.2. Food processing industry

Around 40 % of all seaweed production is utilized by the food processing industry which heavily relies on three seaweed extracts (agar, alginates, and carrageenans) as thickening, stabilizing, clarifying, whipping, emulsifying, and gelling agents (Li and Nie, 2016; World Bank, 2016). These three extracts belong to a group of compounds known as 'hydrocolloids' (or 'phycocolloids' when they are sourced from seaweeds and plants) which readily disperse in solutions and promote gel formation. Only red and brown seaweeds are commercially important sources of hydrocolloids (Glicksman, 1987; Khalil et al., 2018). As detailed in this section, these three extracts have very different properties and, therefore, different markets and commercial applications within the food processing industry.

5.2.1. Agar (extracted from red seaweeds)

Agar is a mixture of two polysaccharides[9], agarose and agaropectin, which are extracted from the cell walls of red seaweeds[10]. Approximately 70 % of the mixture is comprised of agarose, which is responsible for its gelling properties, while the rest is made of agaropectin which is responsible for its thickening properties (Armisen and Galatas, 1987; Armisén and Galatas, 2009).

The food processing industry uses around 80 – 90 % of all agar production in the world. It is primarily used to thicken and stabilize jellies, confectionary, baking products (e.g., icings, glazes, meringues, pastries), canned meats, ice creams, and other dairy products (McHugh, 2003; Pereira, 2011). Agar can also be used to prevent ice crystal formation in frozen goods, and to clarify beer and fruit juices (Cikoš et al., 2021). The most purified grades of agar can sell for a very high price compared to food grade agar, and are usually reserved for molecular biology applications (see Section 5.3). The advantages of using agar to other commercial hydrocolloids (e.g., gelatin) include: (1) it is vegan; (2) it does not require the addition of salts (e.g., potassium and calcium) to achieve gel formation; (3) it can form strong and rigid gels at concentrations as low as 0.5 %; and (4) it can form gels at room temperature yet which can hold their structure in temperatures as high as 65 °C [11] (Rhein-Knudsen et al., 2015; Khalil et al., 2018).

Seaweeds of the genera *Gracilaria* and *Gelidium* are the dominant seaweeds used for industrial agar extraction (Bixler and Porse, 2011). Agar extraction from *Gelidium* predominantly relies on wild seaweeds (Rhein-Knudsen et al., 2015), while *Gracilaria* agar extraction is increasingly utilizing cultured seaweeds due to increased demand and depleted wild sources (Buschmann et al., 2001; Delaney et al., 2016).

[9] Polysaccharides are long-chained carbohydrates such as starch, glycogen, and cellulose.
[10] Agar yielding seaweeds are known collectively as 'agarophytes'.
[11] Agar gels typically have a melting point of 85 – 95 °C.

Like all the seaweed hydrocolloids described in this report, agar extraction is time consuming and expensive (reviewed by McHugh, 2003). In general, *Gelidium* seaweeds are washed and cleaned before the agar is extracted into pressurised hot water (105 – 110 °C) for 2 – 4 hours. In contrast, *Gracilaria* must undergo an alkaline treatment prior to extraction otherwise its gel strength is typically too low for most commercial applications. For this process, the *Gracilaria* is immersed in a heated (85 – 90 °C) alkali solution (2 – 5 % sodium hydroxide) for one hour. It is then washed again, sometimes with weak acid to neutralize any residual alkali before the agar is then extracted in hot water (95 – 100 °C) for 2 – 4 hours. For both species, the resulting extract is then filtered and cooled to a gel containing approximately 1 % agar. The remaining 99 % of the gel is comprised of water which may contain salts, soluble proteins, carbohydrates, and other matter. As a result, the gel may then be bleached and treated further to remove some of these impurities. The remainder of the process is then solely aimed at removing the excess water from the gel.

There are several methods to remove water from agar gel, however, most processors now use freeze-thaw and press / syneresis technologies (reviewed in McHugh, 2003; Bixler and Porse, 2011). Typically, the agar is repeatedly frozen and thawed to dewater the gel (Gioele et al., 2017). Specialised hydraulic presses lined with porous cloths are then used to exert increasing pressure on the agar for around 24 hours, which increases agar content to around 20 %. Finally, the gel is shredded and dried in a hot oven before being milled to a suitable and uniform particle size. Agar can also be processed into squares or long thin strips, sometimes called 'natural agar' (Bixler and Porse, 2011). Overall, the energy, water, and waste disposal costs associated with agar extraction and processing are very high. It is therefore unlikely to be economically viable at small-scales.

5.2.2. Carrageenan (extracted from red seaweeds)

Carrageenans are also extracted from red seaweeds and primarily consist of potassium, sodium, magnesium, and calcium salts of sulfated esters of galactose (another polysaccharide; reviewed in Khalil et al., 2018). As carrageenans can bind water efficiently while thickening, stabilizing, and improving the appearance and texture of foods, they are used in many different products including ice-cream, jellies, baby formula, jam, bread, cheese, syrups, sauces, and processed meats (reviewed in McHugh, 2003).

There are three types of carrageenan which have very different properties and, therefore, different commercial applications:

1. **Kappa carrageenan** forms rigid, brittle gels and are the most valued in food processing;
2. **Iota carrageenan** forms clear, elastic, freeze-thaw stable gels; and
3. **Lambda carrageenan** forms highly viscous liquids but are rarely extracted and used on a commercial scale (Bixler and Porse, 2011).

Different seaweeds tend to contain different types of carrageenan. For example: *Eucheuma spp.* mainly contain iota carrageenan; *Kappaphycus spp.* mainly contain kappa carrageenan; *Chondrus* and *Gigartina spp.* contain a mixture of kappa and lambda carrageenans; while *Sarcothalia spp.* contain a mixture of kappa and lambda carrageenan. Most commercial carrageenan extraction uses cultivated species of *Kappaphycus* (kappa carrageenan) and *Eucheuma* (iota carrageenan) grown in the Philippines, Indonesia, and Tanzania. On a smaller scale, wild *Sarcothalia* and *Gigartina* are harvested in Chile and Mexico, while *Chondrus* is wild harvested in Atlantic Canada and France (McHugh, 2003; Bixler and Porse, 2011).

Prior to the 1980s, 'refined' or 'filtered' carrageenan was the only commercially produced carrageenan (reviewed in McHugh, 2003). The first step in its production involves washing the seaweed and then immersing it in a heated alkaline solution to increase gel strength. Residual seaweed particles are then removed by centrifugation and / or filtration, followed by pressure filtration in combination with a filter aid. At this stage, the liquid solution contains 1 – 2 % carrageenan which can be increased to 2 – 3 % by vacuum distillation and ultrafiltration. Two methods can then be used to further increase the solid content: (1) an alcohol-precipitation method, which can be used for all types of carrageenan. For this process to be economical, the alcohol must be recovered and recycled; or (2) for kappa carrageenan, press / syneresis and / or freeze-thawing may be used (see Section 5.2.1). For the freeze-thaw process, it is convenient to form the gel as spaghetti-like strands by forcing the carrageenan solution through fine holes (i.e., 'extrusion) into a potassium chloride solution. These strands are then washed, pressed, and frozen. Due to similarities in equipment and processing, many agar processors now produce kappa carrageenan as well.

A second extraction method was developed in the 1980s which almost exclusively uses *Kappaphycus alvarezii* to produce kappa carrageenan. For this, the seaweed is heated in an alkaline solution of potassium hydroxide for approximately two hours. This step causes any soluble proteins, carbohydrates, and salts within the seaweed to dissolve into the solution. The residual seaweed, which is now comprised mostly of carrageenan and cellulose, is then simply washed, dried, ground to a powder, and sold as semi-refined carrageenan (SRC) or 'seaweed flour'. As the carrageenan is never extracted from the seaweed, there is no need for any equipment to refrigerate, freeze, and dewater gels, nor any alcohol and recovery / recycling equipment. Consequently, this process is much quicker and cheaper than refined / filtered carrageenan. However, SRC is usually coloured and has a high bacterial count, making it unsuitable for human consumption. Nonetheless, it has a large market in canned pet foods because it makes a good gelling agent and is much cheaper than refined / filtered carrageenan. Also, the temperatures used in the canning process destroy any bacteria so SRC's high bacterial count is usually not considered a problem.

Sometimes SRC is simply chopped into pieces (i.e., it is not milled into a powder) and sold as a raw material to refined / filtered carrageenan processors. This raw material is often called 'alkali treated cottonii' (ATC), 'alkali treated cottonii chips' (ATCC), or simply 'cottonii chips'. These chips are usually processed in the same country that the seaweed was harvested (e.g., Philippines or Indonesia) and then shipped to refined / filtered carrageenan processors in other countries (e.g., in Europe or the USA). These processors then benefit from having skipped several of the processing steps, resulting in lower waste treatment costs and cheaper transport costs than if they imported and processed raw seaweed, which is bulkier and heavier.

5.2.3. Alginate (extracted from brown seaweeds)

Alginate, sometimes called 'algin', is extracted from the outer cell walls of brown seaweeds (Khalil et al., 2018). At low concentrations, alginates can function as a gum to increase the viscosity of liquids. At higher concentrations, alginates can stabilize dispersions such as gels, emulsions, and foams, making them highly desirable and versatile in food industry applications, and in some cases, can provide an alternative to animal-based gelatins. Alginates can also form thermo-reversible gels (i.e., a gel that melts at high temperatures and cools back into a gel). As a result, they are widely used by the food industry for a variety of purposes including to: thicken and stabilise drinks, ice creams and desserts; create foam in mass produced beers; and act as a binder / filler in meat products (reviewed in Delaney et al., 2016; Cikoš et al., 2021).

Alginates are salts of alginic acid (another polysaccharide) and are composed of varying proportions of mannuronic (M) and guluronic (G) acids which are structurally arranged in repetitive blocks. The ratio of M to G varies between seaweed species, age, tissues, and extraction processes, and has a major influence on its physicochemical properties and potential commercial applications (reviewed in Delaney et al., 2016; Cikoš et al., 2021). Typically, higher G content results in more rigid, brittle gels, while higher M content results in greater gel flexibility (Szekalska et al., 2016; Fertah et al., 2017; Khalil et al., 2018). The alginate industry predominantly relies on wild seaweeds belonging to the genera *Ascophyllum*, *Eisenia*, *Laminaria*, *Lessonia*, *Nereocystis*, and *Macrocystis* (Gioele et al., 2017; Alba and Kontogiorgos, 2019). However, over the last two decades, *Laminaria* (cultivated and wild harvested) and *Lessonia* (primarily wild harvested) have come to dominate the alginate industry due to their high G content and high gel strength (Bixler and Porse, 2011).

When used in the context of seaweed, the term 'alginate' usually refers to the calcium, magnesium, and sodium salts of alginic acid. As the calcium and magnesium forms do not dissolve in water, a series of complex steps are taken during alginate extraction to convert them into the soluble sodium form (reviewed in McHugh, 2003; Khalil et al., 2018). Firstly, the seaweed is broken into pieces and stirred with a hot alkali solution, usually sodium carbonate, for about two hours. As darkly coloured seaweeds (such as *Ascophyllum*) yield dark alginate, they may be bleached or pre-treated with formalin during the alkali extraction. The resulting slurry is then filtered using cloths. Large quantities of water, filter aids (diatomaceous earth) and / or air bubbles are used to aid this process. Alginate is then precipitated from the filtrate using one of the two following methods:

- **Alginic acid method.** Adding acid to the filtrate forms soft, gelatinous pieces of alginic acid that can be separated from the water using floatation. These solids are then centrifuged to increase solid content from around 2 to 8 %. Alcohol is then added, followed by sodium carbonate, to convert any other alginate salts to sodium alginate.
- **Calcium alginate method.** Adding a soluble calcium salt, such as calcium chloride, to the filtrate while carefully mixing the solution results in fibrous strands of calcium alginate. These fibres are then sieved, washed with water, and stirred in a dilute acid. A screw press is then used to slowly increase pressure and force water from the solids, resulting in 20 – 25 % alginic acid content. Sodium carbonate is then added to convert it to sodium alginate.

Finally, the resulting pastes are extruded as pellets, which are oven dried and milled to a fine powder. Overall, the extraction process is expensive in terms of time, materials, water usage, and waste disposal.

5.3. Pharmacy and biotechnology industries

The binding and gelling properties of seaweed hydrocolloids are highly important to the pharmaceutical and biotechnology industries for use as: binding agents for pills / tablets / capsules, wound dressings, and dental moulds; and as a culture medium (e.g., agar gel[12]) for bacteria, antibodies, steroids, and alkaloids[13]. The most purified grades of agar (usually agarose) are usually reserved for molecular biology applications such as electrophoresis, immune diffusion, and gel chromatography (Khalil et al., 2018). Lastly, as summarized in Section 5.1.2, seaweeds contain bioactives / nutraceuticals that may be of benefit to human

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[12] About 16 % of agar production in the USA is used as a culture medium.

[13] Well-known alkaloids include morphine, quinine, and nicotine.

health. These are currently the focus of much research to determine their potential commercial applicability (reviewed in Holdt and Kraan, 2011; Cherry et al., 2019b; Shannon and Abu-Ghannam, 2019).

5.4. Cosmetics industry

Seaweed hydrocolloids are often used to emulsify and stabilize cosmetic products such as toothpastes, moisturizers, shampoo, and hair conditioners (reviewed in Cikoš et al., 2021). In addition, seaweed bioactives are also used in cosmetic products for: anti-aging; anti-cellulite; moisturizing; skin-whitening; ultraviolet radiation protection; and reducing the appearance of dark circles around the eyes.

5.5. Agriculture

5.5.1. Crop farming

Seaweeds have been used as fertilizers, compost, and manure for centuries (Verkleij, 1992; Nabti et al., 2017; Zafar et al., 2022). In addition to directly providing nutrients to crops, a rapidly growing body of research suggests seaweeds can benefit agriculture in a variety of other ways. For example, when applied to crops and soils as finely chopped powders or liquid extracts, seaweed bioactives and plant hormones (or 'phytohormones' [14]) can enahnce crop germination, root formation, growth, nutrient uptake, stress tolerance (e.g., to disease, drought, frost, or high salinity), and greater consistency in product size and quality (reviewed in Michalak and Chojnacka, 2015; Nabti et al., 2017). Their application to soils can also promote the growth of bacteri, which can absorb excess nitrogen and phosphorus, thereby reducing nutrient run-off, which is a contributor to eutrophication (see Section 6.1.1). Lastly, seaweed alginates can react with metals in the soil to form long chain polymers, which can help bind soils, improving its crumbling and moisture-retaining properties (reviewed in Abdel-Razek et al., 2011; Pati et al., 2017).

5.5.2. Livestock farming

Seaweeds show great potential as an ingredient in animal feeds as they are low-cost and high in nutrients (for a comprehensive review, see Morais et al., 2020). When used in chicken feeds, evidence suggests seaweeds can improve egg production and quality by increasing shell thickness, reducing cholesterol, improving yolk colour, lowering bacterial loads, and increasing lipid and fatty acid content. The use of the red seaweed, *Asparagopsis armata*, in animal feeds has also been shown to greatly reduce methane emissions[15] by cows, sheep, and goats. However, seaweeds can be high in salt, iodine, and heavy metals, meaning there is potential for toxicity and bioaccumulation effects (also see Section 5.1.2). In addition, livestock sometimes display a strong preference for feeds that do not contain seaweeds. Consequently, more research is needed into the potential positive and negative effects of using seaweed in animal feeds.

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[14] Phytohormones control all aspects of a plant's growth, development, and reproduction. They also regulate pathogen defence and stress tolerance. Unlike in animals (in which hormone production is restricted to specialized glands), each plant cell is capable of producing phytohormones.

[15] Methane is one of the most important greenhouse gasses contributing to climate change (IPCC, 2014).

5.6. Other uses

There are many other potential uses for seaweeds and their extracts including: biofuels (see Section 6.1.4); biodegradable food packaging (Wang and Rhim, 2015); in the creation of textiles, paper and electrodes (Cardozo et al., 2007; Bixler and Porse, 2011); as a component of sodium-based batteries, which has potential to supersede lithium-based batteries in electric vehicles (Sparkles, 2022); and in water remediation to remove heavy metals, nitrogen and phosphorus in effluents of wastewater treatment plants and other industrial practices (Patra et al., 2016; Gioele et al., 2017; Khalil et al., 2018), including integrated multitrophic aquaculture (for examples of IMTA, see Section 7.4 and Section 7.5).

6. Seaweed aquaculture and the environment

As open-water seaweed aquaculture typically does not require feeds, fertilizers, or therapeutants (i.e., pesticides, herbicides, and veterinary drugs), it is widely perceived as one of the most environmentally benign forms of aquaculture (reviewed in Cottier-Cook et al., 2016). However, seaweed aquaculture can interact with the environment in many ways. As the following section details, most of these interactions may be perceived as being neutral or positive, but others may be perceived as negative.

6.1. Potentially positive impacts

6.1.1. Eutrophication mitigation

A wide range of human activities (e.g., agriculture, aquaculture, urbanisation, and industrialisation) release nutrients into coastal waters (reviewed in Nixon, 1995; Smith, 2003; Halpern et al., 2019). Elevated concentrations of nitrogen and phosphorus are of particular concern as they can contribute to 'eutrophication'. This is when high nutrient levels stimulate large blooms of phytoplankton and aquatic plants. When this organic matter begins to decompose, it can promote oxygen depletion in surrounding waters and sediments, causing an overall loss in biodiversity (Nixon, 1995; Howarth et al., 2011). However, as seaweeds rapidly absorb and accumulate nitrogen and phosphorus from the surrounding water into their tissues (Howarth et al., 2020), seaweed aquaculture could remove substantial quantities of nutrients from coastal waters (Zheng et al., 2019). Thus, mid- to large-scale seaweed aquaculture has been proposed as a potential tool to mitigate eutrophication.

China's coastal waters are subject to some of the world's largest inputs of anthropogenic nitrogen and phosphorus due to intensive levels of industry, agriculture, and urbanisation (Boyer et al., 2006; Tysmans et al., 2013). However, China also has the world's largest seaweed aquaculture industry, both in terms of production and spatial coverage (also see Section 3.1). Thus, 5.6 % (75,000 tonnes) of all nitrogen inputs and 40 % (9,500 tonnes) of all phosphorus inputs are estimated to be removed each year by seaweed aquaculture in China (Xiao et al., 2017). Furthermore, it is expected that seaweed aquaculture will be able to remove 100 % of all anthropogenic phosphorus inputs by the year 2026, based on current rates of seaweed industry growth (Xiao et al., 2017). In contrast, the complete removal of nitrogen would require a 17-fold increase in seaweed aquaculture. These projections are supported by field studies which have observed decreased concentrations of nitrate, ammonium, and phosphate, and slight increases in oxygen, at multiple seaweed aquaculture sites in China compared to reference areas (e.g., He et al., 2008; Wu et al., 2015; Jiang et al., 2020). Consequently, it has been argued that Chinese seaweed aquaculture has already reached a scale where it is greatly benefiting the environment through eutrophication mitigation (Xiao et al., 2017).

6.1.2. Carbon sequestration

Due to the burning of fossil fuels (i.e., petroleum, natural gas, and coal) and other human activities, atmospheric concentrations of CO_2 are the highest they have been for at least 2 million years (IPCC, 2014; IPCC, 2021; NASA, 2022). As CO_2 is one of the primary greenhouse gasses contributing to climate change, capturing and storing (or 'sequestering') some of this excess CO_2 is widely considered to be one of the only viable, short-term solutions to mitigating climate change (reviewed in Wennersten et al., 2015).

Carbon sequestration aims to capture CO_2 (and potentially other carbon-based compounds) from the environment and then securely store it over a geologically significant timescale; usually defined as a minimum of 100 years (GESAMP, 2019). For example, protecting forests and planting trees is commonly advocated as an effective carbon sequestration tool because trees directly absorb CO_2 from the atmosphere (reviewed in Waring et al., 2020). Although trees re-emit half of this carbon as CO_2 during respiration (also see Section 1.4), the remainder can become locked within their tissues (e.g., trunks, branches, leaves, and roots) for several centuries. Furthermore, the carbon stored within any harvested timber and fallen logs and can persist for several more centuries, while the carbon stored within any fallen litter (e.g., leaves and fruits) can become incorporated into soils and persist for over a thousand years[16]. Likewise, mangroves, seagrasses, and other forms of 'blue carbon', have also been argued to be able to sequester carbon within their tissues, roots, rhizomes, and underlying sediments (reviewed in Taillardat et al., 2018; Bedulli et al., 2020).

Recently, an increasing number of environmental organizations, advisory groups, and scientists, have advocated for the global expansion of seaweed aquaculture to further sequester carbon (e.g. World Bank, 2016; The United Nations, 2020; Duarte et al., 2022). Furthermore, several authors have even proposed sinking large quantities of cultured and wild seaweeds to the deep ocean (e.g. Froehlich et al., 2019). However, these strategies lack a body of evidence to evaluate their effectiveness, and the potential risks or co-benefits they may have on ecosystems. Consequently, many scientists argue that the ability of seaweeds to sequester carbon is highly uncertain (see reviews by Gallagher et al., 2022; Hurd et al., 2022; Troell et al., 2022). Their reasons for this include:

1. **Seaweeds lack roots and rhizomes.** As a result, they do not accumulate and trap organic material in underlying sediments like trees, mangroves, and seagrasses.

2. **Rapid tissue turnover.** Most seaweeds only live for 0.5 – 7 years. During this time, they consistently lose tissues and biomass (and the carbon stored within) to the external environment through processes such as growth, reproduction, and weather and wave-driven erosion.

3. **Seaweeds take up CO_2 from seawater, not the atmosphere.** The removal of this CO_2 creates an imbalance in the equilibrium between the atmosphere and ocean. However, as the timescale of this re-equilibration ranges from weeks to years, the seaweed-driven removal of CO_2 from the oceans

[16] Globally, the upper 1 m layer of soil stores approximately three times more carbon than currently present in the Earth's atmosphere (FAO, 2015).

may not necessarily equate to the removal of CO_2 from the atmosphere. Overall, these processes are highly complex, poorly understood, and require further investigation.

6.1.3. Buffering ocean acidification

When seawater absorbs CO_2, a series of chemical reactions are triggered which increases its acidity and lowers its pH (Doney et al., 2009). As the oceans have absorbed approximately 30 % of all the CO_2 emitted since the industrial revolution (also see Section 6.1.2), they have experienced a 26 % increase in acidity and a pH reduction of 0.1 (Rhein et al., 2013; IPCC, 2014; IPCC, 2021). This process, known as 'ocean acidification', reduces the availability of carbonate ions and calcium carbonate minerals which are needed by some marine organisms to grow their skeletons and shells (Doney et al., 2009; Billé et al., 2013). Consequently, ocean acidification can negatively impact the growth and survival of bivalves (e.g., scallops, clams, oysters, and mussels), crustaceans (e.g., lobster, crab, and shrimp), corals, plankton, calcifying algae (e.g., coralline algae) and calcareous seaweeds (e.g., maerl and *Corallina officinalis*). However, some species of phytoplankton, seagrass, and seaweed (particularly non-calcifying species) have been shown to exhibit faster growth rates in CO_2-elevated environments (reviewed in Young and Gobler, 2018; Gao, 2020).

As seaweeds and other aquatic plants absorb CO_2 during photosynthesis (see Section 1.4), they can increase the pH of the surrounding water and increase carbonate availability. Thus, a growing number of laboratory studies have shown that the co-culture of seaweeds and bivalves can buffer elevated CO_2 levels and improve bivalve survival and growth (e.g., Young and Gobler, 2018; Young et al., 2022). However, field evidence supporting this notion is still greatly lacking. Furthermore, some of the absorbed CO_2 will inevitably be released back into the water during respiration at night (see Section 1.4), potentially negating any influence they have on buffering ocean acidification (e.g., Fernández et al., 2019; Gao and Beardall, 2021).

6.1.4. Seaweeds as biofuels

Not only are fossil fuels non-renewable sources of energy, their extraction, processing, and combustion releases greenhouse gasses and other pollutants into the atmosphere, which are associated with a wide variety of environmental and health impacts (IPCC, 2021; IPCC, 2022). Thus, in attempt to reduce fossil fuel dependency, many governments (e.g., USA and the EU) have been supporting the production of renewable, biologically-sourced fuels (or 'biofuels') since the early 2000's (reviewed in Su et al., 2015).

Biofuel is the name given to any solid, liquid, or gaseous fuel derived from animal and plant materials (reviewed in Vassilev and Vassileva, 2016). Presently, the greatest source of biofuel is ethanol made from the fermentation of starch, sugars, and lipids in crops (e.g., corn, sugar cane, sunflower, soybean, and palm oil), and to a lesser extent, within high-cellulose biomass (e.g., forestry waste, wood chips, and municipal waste). However, the practice of using agricultural crops as biofuels has raised controversy for several reasons, including: (1) it can negatively impact food security and food prices; and (2) its widespread adoption would require an increase in crop production, which would require more land to be converted to farmland, which would exert more pressure on terrestrial ecosystems and limited freshwater resources. In contrast, using seaweeds as biofuel may have several advantages to crops, including: (1) seaweeds typically do not require freshwater, fertilizer, or land; (2) they have fast growth rates; and (3) they can be grown in low productive, degraded, or contaminated waters. However, cultivating, harvesting, processing, and transporting seaweeds for biofuel production is substantially more expensive than using agricultural crops and other terrestrial materials (reviewed in Vassilev and Vassileva, 2016). In addition, the processing, fermentation, and combustion of plant and seaweed-derived biofuels may release more CO_2 than is absorbed during their growth (e.g. DeCicco et al., 2016). Overall, seaweed biofuel research is still in its infancy and the industry requires substantial technological development and innovation (Chen et al., 2015).

6.1.5. Habitat provision

A wide diversity of fish and invertebrate species are known to use wild seaweed communities as habitat (reviewed in Theuerkauf et al., 2021). In addition, fish are well known to aggregate underneath floating objects (e.g., oil platforms, wharves, natural debris / flotsam), including shellfish and finfish farms (Dempster et al., 2004). Therefore, seaweed farms will likely promote fish aggregations and provide habitat to a diversity of species (Campbell et al., 2019). In support of this, a large number of studies have observed greater abundances and diversity of fish and invertebrates near seaweed / and or shellfish farms compared to reference areas (reviewed in Theuerkauf et al., 2021). However, cultured seaweeds can be associated with different communities of organisms compared to naturally occurring seaweeds (e.g. Walls et al., 2016), likely because of their unnatural suspension above the seabed, and their placement in greater water depths over different sediments (reviewed in Campbell et al., 2019).

6.2. Potentially negative impacts

6.2.1. Seaweeds as a source of particulate organic matter (POM)

Seaweed tissues continually breakdown and enter the environment through natural processes such as growth, reproduction, senescence, and weather / wave-driven erosion. Known as 'particulate organic matter' (POM), seaweed-derived POM is an important and natural contributor of carbon to coastal ecosystems (Leclerc et al., 2013). However, the excessive release of POM from large-scale seaweed farms could potentially lead to enhanced microbial decomposition and localized oxygen depletion within sediments and the water column (reviewed in Campbell et al., 2019). Some evidence suggests that the release of POM from seaweed farms will fluctuate seasonally, typically being higher during harvesting and maintenance activities, during the early stages of growth, and later on in the growing season when heavy biofouling and tissue degradation can cause the rate of tissue loss in kelp to surpass the rate of tissue growth (Zhang et al., 2012; Fieler et al., 2021). Overall, greater scientific investigation into the extent and fate of POM derived from seaweed aquaculture could help provide context on what scale of activity and environmental conditions are likely to cause significant environmental impacts (Campbell et al., 2019).

6.2.2. Competition for light and nutrients

Open-water seaweed aquaculture uses buoys, ropes, moorings, and other site infrastructure which can restrict the amount of light penetrating through the water and on to the seafloor. This shading could have negative effects on the growth and survival of wild aquatic plants (e.g., seaweeds, seagrass, and potentially phytoplankton) growing within the vicinity of the operation (reviewed in Wu et al., 2016; Campbell et al., 2019). Furthermore, seaweeds rapidly absorb nutrients (e.g., nitrogen, phosphorus, potassium, and sulphur) from the surrounding water, which could reduce the amount of nutrients available to phytoplankton and wild aquatic plants (Lüning and Pang, 2003; Marinho et al., 2015), potentially affecting the base of marine food webs. Nonetheless, it is considered unlikely that small and mid-scale seaweed farms will significantly compete with native plants and plankton for light and nutrients (reviewed in Campbell et al., 2019).

6.2.3. Genetic contamination of wild populations

Hatchery-reared seaweeds (see Section 7.1.3 for an example) may become genetically distinct from wild populations, especially when strains with desirable traits (e.g., greater size, growth, nutrient content, and disease resistance) are actively selected and maintained (Valero et al., 2017), which could reduce their genetic diversity. Once these cultivated strains are moved to open water, they could release genetic material (e.g., spores and gametes) into the surrounding environment, which could theoretically compete and / or crossbreed with native populations. The effects of such gene flow from cultivated seaweeds are currently unknown but could potentially be mitigated through responsible breeding practices (reviewed in Cottier-Cook et al., 2016; Campbell et al., 2019).

6.2.4. Non-native and invasive species

There are many instances where non-native species of seaweed have been introduced to the wild (both unintentionally and purposefully) which now compete with native flora and fauna (e.g. Fletcher and Farrell, 1998; Smith et al., 2004; Williams and Smith, 2007; Kraan, 2017). In Canada, multiple national and regional legislation and programs aim to prohibit or prevent unintentional or illegal species introductions (reviewed in Reid et al., 2021). Specifically, the *Aquatic Invasive Species Regulations* (SOR/2015-121), made under the Federal *Fisheries Act* (R.S.C., 1985, c. F-14), prohibits the introduction of non-indigenous species into the aquatic environment. As a result, the aquaculture of non-native seaweeds is not permitted in Canadian waters and, therefore, is unlikely to be an issue. Introducing genetically non-local strains of seaweeds to other regions is also restricted under provincial regulations in Nova Scotia (see Section 8.5).

6.2.5. Other potential ecological impacts

Like other forms of open-water aquaculture, the maintenance and harvesting activities associated with seaweed aquaculture can require human presence and generate noise, which could potentially disturb birds and other wildlife in the area. Likewise, gear and site infrastructure (e.g., ropes, anchors and moorings) could pose a potential entangling risk to marine mammals. However, there are mitigation measures that can reduce whale entanglements, such as using ropes with lower breaking strengths. In addition, the risk of all these potential ecological impacts is evaluated before aquaculture licenses and leases are granted in Nova Scotia (see Section 8).

7. Opportunities and barriers for seaweed aquaculture in Nova Scotia

This section summarizes the biology, production and processing methods, and opportunities and barriers, associated with several species of seaweed that are likely suitable for culture in Nova Scotia. Much of the following information is adapted from Redmond et al. (2014), and to a lesser extent, Flavin et al. (2013).

7.1. Kelp (brown seaweeds)

The only seaweed species currently being cultured in open water within Atlantic Canada are *Saccharina latissima* (or sugar kelp, Figure 9A), and to a much lesser extent, *Alaria esculenta* (or winged kelp, Figure 9C, also see Section 4.3). *Laminaria digitata* (or horsetail / oarweed, Figure 9B) also has strong potential for culture but is not currently being farmed in Atlantic Canada. All three kelps can be used in cooking (some companies even refer to these species as 'Atlantic kombu' or 'Atlantic wakame') and tend to be very high in fiber, vitamins, and minerals (see Table 2). Although all three species can provide a source of alginate (see Section 5.2.3), they are not the predominant species currently being utilised by the alginate extraction industry (Fertah et al., 2017; Saifullah et al., 2021; Cebrián-Lloret et al., 2022).

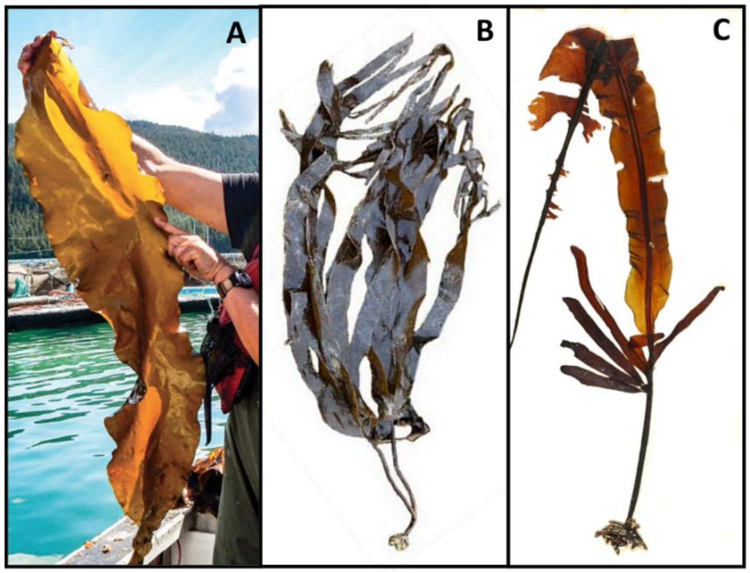

Figure 9 | The three species of kelp most likely to be suitable for culture in Nova Scotia: (A) Sugar kelp (*Saccharina* latissima) has a single blade with no mid rib, however, some variations have a flattened base at each blade, resembling a sheet of lasagna (image from DFO); (B) Horsetail / oarweed (*Laminaria digitata*) has a single blade dissected to various degrees depending on wave action and water currents (image from Wiki Commons); and (C) winged kelp (*Alaria esculenta*) has a single blade, a strong mid rib, and reproductive wing-like appendages, known as 'sporophylls', located near the stipe (image from Wiki Commons).

7.1.1. Distribution and optimal growing conditions

Saccharina, *Alaria* and *Laminaria* inhabit the lower intertidal zone in rocky environments and typically do not occur deeper than 20 m in Nova Scotia. All three species are widely distributed across the Atlantic Ocean. *Saccharina* is also common in the North Pacific, while *Alaria* is also common in the Indian and South Pacific Oceans (OBIS, 2022). Generally, *Saccharina* is found in areas of moderate current and low wave energy, *Laminaria* in high current and moderate wave energy, and *Alaria* in moderate to high currents and high wave energy. Most kelp species exhibit optimal growth at salinities above 15 practical salinity units[17] (PSU) and at temperatures between 10 – 15 °C (Monteiro et al., 2021; MARLIN, 2022).

7.1.2. Biology

Most kelps (or 'Laminariales') have a similar life cycle (Figure 10), which typically alternates between a large, conspicuous phase (i.e., the sporophyte) followed by several microscopic phases (i.e., spores, gametophytes, and gametes). The term 'sporophyte' refers to the reproductive areas on mature blades, known as 'sorus tissue' or 'sori', which generate and release spores into the surrounding water. Sorus tissue is easily

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[17] Seawater tends to be around 35 PSU.

identified as it tends to be thicker and darker than the rest of the seaweed. *Alaria* is different as the spores are produced by small appendages (known as 'sporophylls') located near the stipe. Following their release, kelp spores drift and quickly settle on to the seafloor where they develop into male or female gametophytes. The female gametophytes then begin producing and extruding eggs, and secreting a hormone which attracts sperm released from male gametophytes. Any fertilized eggs then develop into juvenile sporophytes, which usually occurs directly on top of the gametophyte.

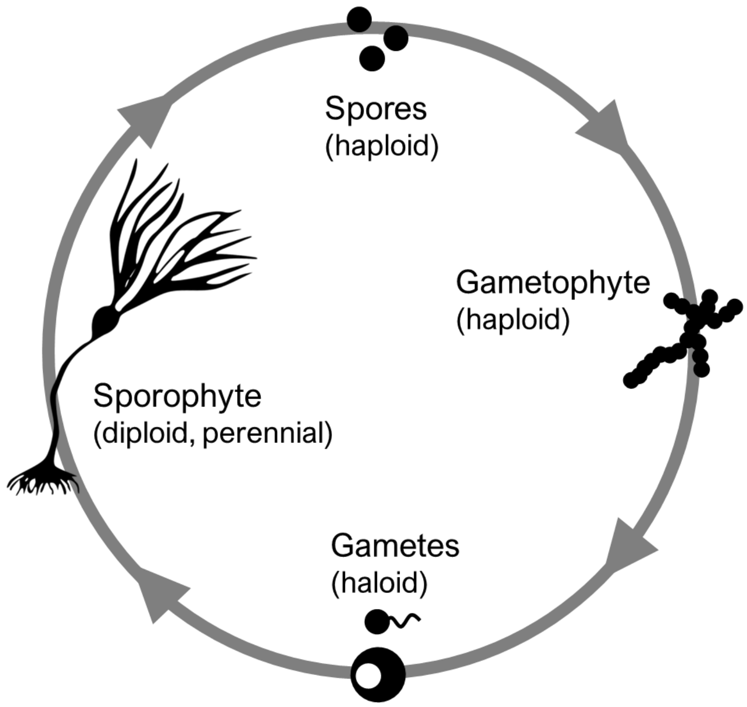

Figure 10 | The simplified life cycle of typical kelp species.

All three species are 'perennial', meaning they persist for multiple years. However, *Saccharina* is the most short-lived, rarely persisting for more than two years, while *Laminaria* is the longest-lived, capable of persisting for four years or more. All display similar blade growth patterns, with the highest rates of growth occurring during the winter months and first half of the year. Sorus tissue development then peaks in the fall and again during the following spring. New growth primarily occurs above the stipe, allowing for the shedding of old tissues (often fouled with epiphytes) at the top of the blades.

7.1.3. Lab culture

Kelp aquaculture typically involves planting seeded lines in open water (see Section 7.1.4). Seeded lines are created in land-based hatcheries and can either be sourced from specialized companies (e.g., GreenWave supply seeded lines to the majority of kelp growers in Southern New England) or new hatcheries can be created by growers relatively easily providing they have the required equipment and technical expertise.

The production of seeded lines tends to follow one of two methods. The first method involves extracting sorus tissue from kelp (usually wild harvested) in a sterile laboratory. The sorus tissue is then gently desiccated and cooled to stimulate spore release. The spores are then added to tanks containing synthetic, multi-filament 'seed string' (or 'seed twine') wrapped around several PVC pipes (often known as 'nursery' or 'seed spools', see Figure 11A). The spores then settle on to the seed string where they begin to develop into gametophytes. The gametophytes develop into juvenile sporophytes within 2 – 3 weeks, appearing as a 'brown fuzz' (Figures 11B and 11C). The seed spools are then ready for transport into the field for grow out. For transport, the seed spools are placed inside cooled, sealed containers to reduce light and heat stress, and physical damage.

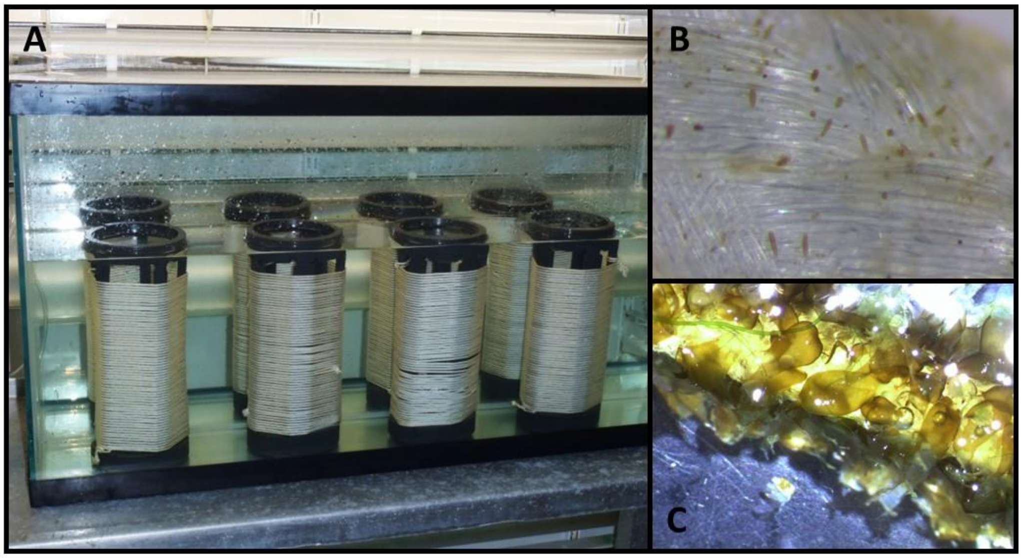

Figure 11 | (A) Seed string wrapped around several seed spools; (B) Seed string seeded with newly settled juvenile sporophytes; and (C) Seed string seeded with sporophytes mature enough to be transported into the field for grow out. Images provided by Merinov.

In comparison, the second (or 'European') method requires more laboratory space and specialized equipment to isolate and vegetatively clone male and female gametophytes. These can then be preserved in a non-reproductive state for several months to a year before being mixed to sexually reproduce and generate seed spools. This method has the advantage of providing a reliable source of seed, available year-round, while also allowing for greater genetic control of the strain being cultured. However, the disadvantage of this method is that gametophytes (compared to spores in the first method) exhibit less settlement / attachment success to seed string, and more energy and equipment is required to maintain vegetative gametophytes at specific light and temperature levels.

7.1.4. Field culture

Most grow out systems for culturing kelp involve suspending horizontal long lines in the water between a series of buoys, weights, and moorings (Figure 12). Seed spools are then uncoiled around the long lines by hand, or by using specialized equipment. As the kelp increases in buoyancy as it grows, additional weights have to be added over time. Overall, the ideal growing depth depends on the season, the species being cultured, and the turbidity of the water.

Figure 12 | Mature kelp sporophytes growing from a suspended long line (Rachelle Hamac / Blue Evolution).

7.1.5. Experimental kelp aquaculture in Cape Breton, Nova Scotia

In 2018, the Aquaculture Association of Nova Scotia (AANS), with the support of Merinov and three industry partners (Premium Seafoods Ltd, Cape Breton Bivalve of Louisbourg Seafoods Ltd, and Bounty Bay Shellfish) acquired funding from Atlantic Canada Opportunities Agency (ACOA) to trial the culture of *Saccharina* in Cape Breton, Victoria, and Richmond counties. This ongoing project has two primary objectives:

1) To test *Saccharina* growth in three different bays (led by Merinov); and
2) To define the primary market and processing needs for Nova Scotian seaweed products (led by Waypoint Business Solutions Inc).

To comply with NSDFA policy on the reintroduction of wild material (see Section 8.5), Merinov collected sorus tissue from wild *Saccharina* growing in each of the three bays in Cape Breton. Merinov then established a hatchery for each strain in their facilities in Quebec. The resulting seeded lines were then transported back to their respective bays in Cape Breton for grow out. Two trials were performed and provided successful yields in 2019-2020 and 2021-2022 at most sites.

One industry partner (Premium Seafoods Ltd) made their second successful harvest in summer 2022. As there are no kelp processing capabilities in Nova Scotia (also see Section 7.1.7 and Section 7.6) the wet kelp was shipped to Maine, USA where it was processed for use in food products. This company has also received funding from Nova Scotia Business Inc (NSBI) to establish a small hatchery in Petit-de-Grat, Cape Breton, in partnership with Merinov and Prof. Michelle Theriault from Université Sainte-Anne (Michelle Samson, Premium Seafoods Ltd, pers. comms, August 2022). Another industry partner, Cape Breton Bivalve, recently acquired an industrial drier and shredder to begin trialing the processing of *Saccharina* (Mike Moore, Cape Breton Bivalve, *pers. comms*, October 2022).

7.1.6. Other kelp operations and projects in Nova Scotia

There are also several other kelp operations and research projects occurring in Nova Scotia. SeaChange Biochemistry Inc. is based in Cape Sable Island, Nova Scotia, and have the capability to produce seeded lines of *Saccharina*. They are also in the process of trialling the production of several other species (Sabrena Mackenzie, SeaChange Biochemistry, *pers. comms*, September 2021). In addition, the company owns a pilot-scale processing facility that is used to extract alginate (see Section 5.2.3), fucoidan, and polyphenols (also see Section 5.1.2) from wild-harvested brown seaweeds (mostly *Ascophyllum*) imported from Scotland, and are currently looking to relocate and expand the facility (Steve Owen, NRC, *per. comms,* September 2022).

A collaborative project between Merinov and the National Research Council Canada (NRC) aims to: (1) define the genetics and morphology of wild *Saccharina* populations in Eastern Canada; (2) develop a seed bank to help preserve valuable ecotypes and populations; (3) select and propagate strains of *Saccharina* which show higher yields, growth, and resilience to climate change and other stressors. This project could also help NSDFA determine how far cultured *Saccharina* seed can be planted from the original source of wild sorus tissue (see Section 8.5).

LeBlanc Seeded Lines is based in West Pubnico and are currently trialling the production of seeded lines of *Saccharina* using different equipment and environmental conditions. The company aim to supply kelp growers in the prospective Lobster Bay ADA (Charlene LeBlanc, LeBlanc Seeded Lines, *per. comms,* September 2022). While, Acadian Seaplants (see Section 4.5.1 and Section 7.2.3) and AANS are trialling the value-added processing of cultured *Saccharina* grown in Cape Breton (see Section 7.1.5).

Lastly, the Ecology Action Centre have partnered with Indian Point Marine Farms Ltd and Perennia Food and Agriculture Corporation for their 'Kelp Kurious' project. The project aims to establish a demonstration farm and nursery for *Saccharina*, and an education / outreach centre. The project will also offer training and support services to prospective seaweed farmers, including navigating processing regulations (see Section 8.6), and supporting nutrient profiling and labelling.

7.1.7. Opportunities and barriers

Of all the seaweed species that have potential for culture in Nova Scotia, kelp aquaculture has the greatest potential for immediate development and expansion. This is because: (1) the life cycle of kelp is relatively simple and well understood; (2) kelp hatcheries are low cost and simple in design; (3) several kelp hatcheries are already being developed across the province; (4) kelp is highly suitable for grow-out in open water, which greatly reduces daily operational costs compared to land-based methods; (5) seeded lines can be easily outplanted on to existing longline shellfish farms; and (6) the industry would not have to compete with wild harvests, unlike other species of seaweed (e.g., see Section 7.3). However, there are at least two major barriers that may impede expansion of the industry:

1. **Limited processing capabilities.** At present, there are no facilities that are processing kelp on a commercial scale in Nova Scotia. Premium Seafoods Ltd (see Section 7.1.5) circumvented this issue by exporting their kelp to commercial kelp processors in Maine. However, this is unlikely to be a long-term viable solution for the Nova Scotian industry as shipping wet product is expensive and logistically difficult. It is also a high-risk strategy as the product must be harvested and shipped within the same day to ensure the product remains fresh during transport.

   It is possible that some companies and growers will be interested in investing in a kelp processing facility in Nova Scotia, providing there is enough raw material and market demand to make such an enterprise profitable. There are approximately 70 facilities licensed for seaweed processing in Nova Scotia (Meredith Fraser, NSDFA, *pers. comms*, September 2022). Only a small proportion of these are actively processing seaweeds and those that are primarily handle wild *Ascophyllum*, and to a lesser extent, wild *Palmaria*. There are also around 200 licensed seafood processing facilities within the province, and many more facilities that process other foods and raw materials. Many of these already have the capability to clean, blanch, dry, mill, and package raw materials, and could potentially be adapted to process kelp into foods and powders. Furthermore, adapting an existing facility for such purposes could be achieved relatively inexpensively. However, they would still have to navigate a potentially complex licencing and regulatory environment (see Section 8.6).

While processing kelp into foods and powders in Nova Scotia could be achieved relatively inexpensively, extracting alginate and other compounds could prove more difficult and costly. Not only would the creation of new extract processing facilities require substantial financial investment, but they would require a constant and high-volume supply of raw materials to ensure long-term profitability. Consequently, current levels of kelp production in Nova Scotia are probably too small to support a kelp extract processing industry without additional financial support or the importation of raw materials from other provinces and / or countries. Furthermore, the methods involved in seaweed extract processing are highly specific to each market. Thus, the industry must identify which markets they intend to target before creating new kelp extract processing facilities. This is a cyclical problem that is common to all seaweeds discussed in this report (see Section 7.6.1).

2. **Limited market access.** Although there are multiple markets for raw and processed kelp, such as the food, pharmaceutical, and alginate industries, it is unclear which markets could be readily accessed by kelp growers and processors in Nova Scotia. In addition, it is unknown how well the industry in Nova Scotia could compete for access to these markets compared to seaweeds from other regions and countries, particularly local, wild, harvested brown seaweeds, such as *Ascophyllum*, which are low cost and highly abundant in supply. This could be a major barrier for kelp growers as poor competitiveness against wild seaweed harvests had large consequences for the land-based aquaculture of *Chondrus* in Atlantic Canada (see Section 7.2.3).

Overall, these barriers of limited processing capability and market access are true for all seaweed species that have potential for culture in Nova Scotia (also see Section 7.6.1).

7.2. Irish moss, *Chondrus crispus* (red seaweed)

Chondrus crispus, commonly known as Irish moss, is a red seaweed that is widely considered to be flavorful and nutritious (Table 2). Although wild *Chondrus* was harvested across Atlantic Canada and New England for many decades to supply the carrageenan extraction industry (Chopin and Ugarte, 2006; Craigie et al., 2019), it is no longer a major supplier since the large-scale aquaculture of *Kappaphycus* and *Eucheuma* was developed in Asia and Africa (also see Section 5.2.2).

7.2.1. Distribution and optimal growing conditions

Chondrus can vary greatly in physical appearance, from small, compact, bushy clumps (Figure 13) to longer and more narrow strands. It can also vary in colour, ranging between yellow, brown, and dark red. Typically though, its gametophyte stage (see Section 7.2.2) is dark red with blue iridescent tips. The species is common in the Atlantic Ocean, and grows on rocks, cobbles, and other hard substrates in depths ranging from the intertidal zone down to 20 metres or more (Prince and Kingsbury, 1973). In North America, its distribution ranges from the Long Island Sound to southern Labrador (reviewed in Wilson et al., 2019).

Growth rates vary greatly across its distribution but typically ranges from 0.3 – 0.4 mm per day (Prince and Kingsbury, 1973; Pybus, 1977).

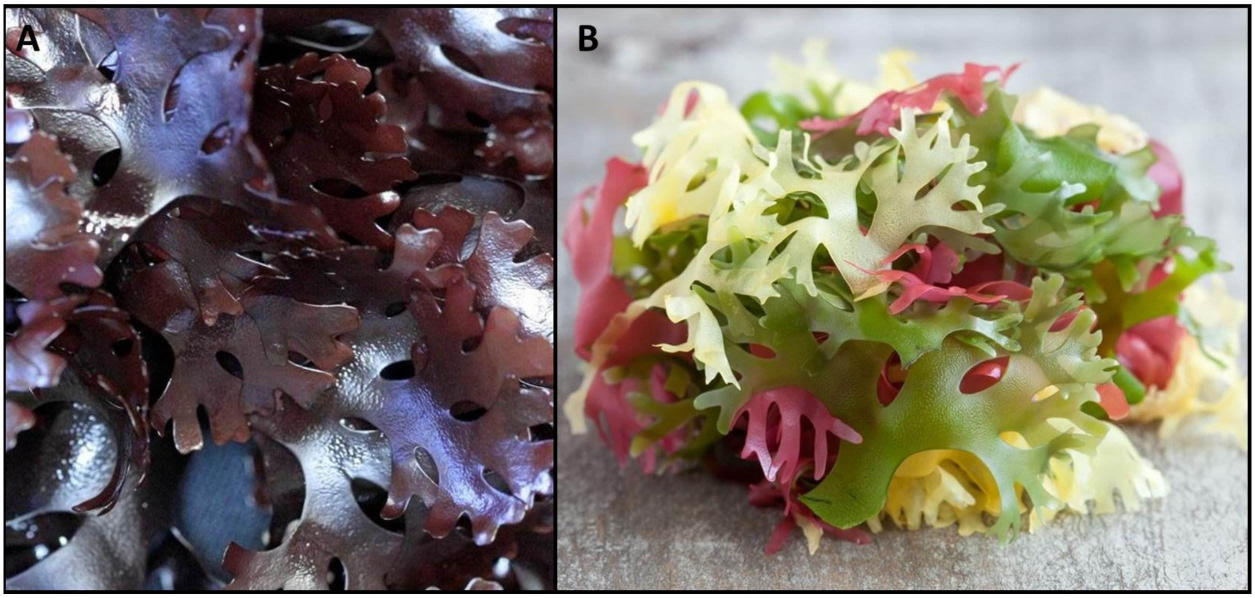

Figure 13 | (A) The gametophytes of Irish moss (*Chondrus crispus*). (B) Hana Tsunomata® is an Acadian Seaplants Ltd. product which has had its colour and texture modified to increase consumer appeal (images provided by Acadian Seaplants Ltd).

Optimal growing temperatures for *Chondrus* are between 10 – 20 ºC but it can survive in temperatures between -1.9 °C and 26 °C (reviewed in Fisheries and Oceans Canada, 2008; Redmond et al., 2014). While it can tolerate a wide range of salinities (10 - 58 parts per trillion / ppt), salinities below 30 ppt can substantially reduce its growth (reviewed in Fisheries and Oceans Canada, 2008). Under laboratory conditions, it reaches a maximum photosynthetic rate at light levels between 200 – 250 µ mol photons m^{-2} s^{-1} (the outside sunlight level at noon during the summer is typically about 2000 µmol photons m^{2} s^{-1}). Interestingly, studies show that growth rates are higher under constant illumination (Neish et al., 1977; Redmond et al., 2014), and that growth and pigment concentrations are higher in land-based tanks when ammonium, phosphates, calcium, and other nutrients are added to seawater in land-based tanks (Neish et al., 1977).

7.2.2. Biology

The life cycle of *Chondrus* is complex but can be divided into three primary phases (Figure 14):

1. **Gametophytes (haploid)** are male or female and large and conspicuous (unlike kelp). Non-mobile gametes (i.e., aplanospores) are released from ‘gametangia’ which appear as white spots on the tips of male blades. After the male gametophytes fertilize female gametophytes, the female blades develop small round bumps called ‘cystocarps’.

2. **Carpospores (diploid)** are released from cystocarps and quickly settle onto hard substrates, such as rocks and shells, before developing into ‘tetrasporophytes’.

3. **Tetrasporophytes (diploid)** look very similar to gametophytes, however, fertile tetrasporophytes develop spotty opaque patches on the blades which contain 'tetraspores'. These tetraspores are then released and attach to hard substrates before developing into male or female gametes. Once the gametes cross-fertilize, they develop into gametophytes.

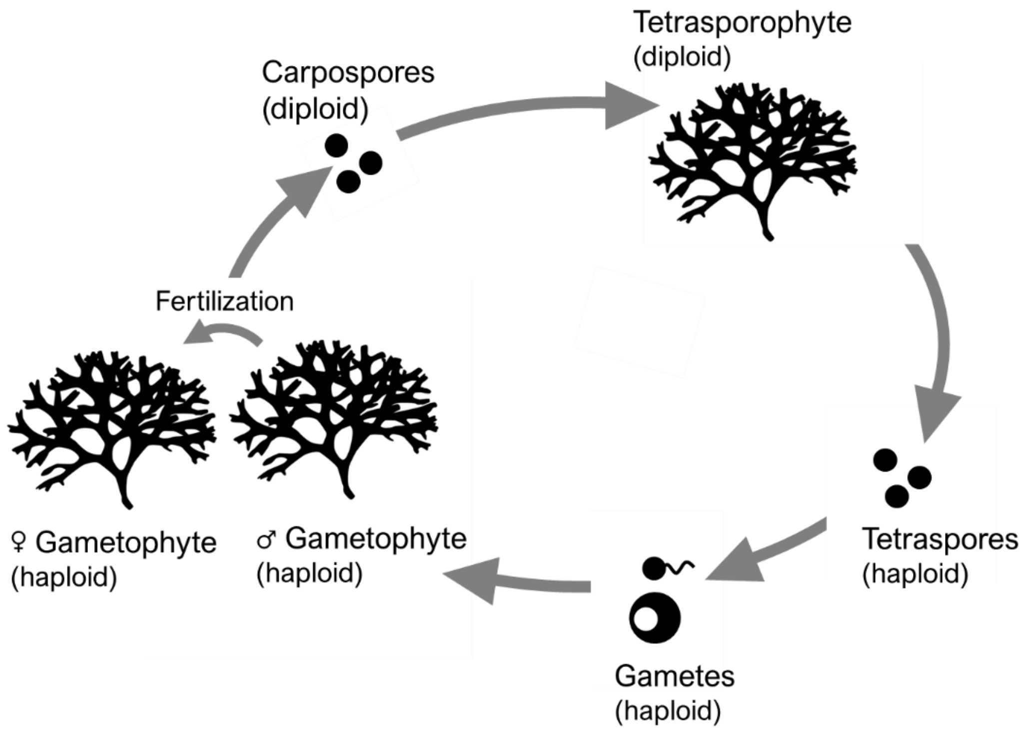

Figure 14 | The simplified life cycle of Irish moss (*Chondrus crispus*).

Chondrus is a perennial species as both the gametophyte and tetrasporophyte stages typically survive for at least two years in the Northwest Atlantic, with most of their growth occurring during the summer months. However, both stages can display markedly different carrageenan composition (McCandless et al., 1973), as gametophytes mostly yield lambda carrageenan, while tetrasporophytes mostly yield kappa and iota carrageenans (Lipinska et al., 2020).

7.2.3. A brief history of land-based Chondrus aquaculture in Eastern Canada

Historically, substantial quantities of wild *Chondrus* were harvested from the Maritime Provinces[18]. Harvest rates peaked between the 1940's – 60's when wild landings increased 34-fold, primarily in response to increased demand for carrageenan (Chopin and Ugarte, 2006). As such high harvest levels were widely considered to be unsustainable, and because carrageenan yields from wild *Chondrus* were inconsistent, a series of research programs were launched between the 1960's – 80's (see Craigie et al., 2019 for a comprehensive review on this topic). These research programs led to the development of outdoor

[18] Wild harvests of *Chondrus* continues to this day at a rate of approximately 2000 metric tons per year in Nova Scotia (Herb Vandermulen, *pers. comms*, November 2022).

cultivation tanks at the NRC Sandy Cove facility, as well as in Meteghan, Nova Scotia, and Pointe-Sapin, New Brunswick. Certain strains of *Chondrus* which exhibited favourable physical appearance and growth rates were selected for culture (Craigie et al., 2019). One of the most successful strains, known as 'T4', is a male gametophyte that does not attach to substrates (Guiry, 1981). It also remains vegetative when being cultured, meaning it does not develop reproductive structures (e.g., cystocarps) which could negatively affect its physical appearance and commercial value.

Although several commercial companies were involved in these projects, only one persisted. This company went on to develop the large outdoor seaweed cultivation ponds at Charlesville, Nova Scotia (Figure 15), and was subsequently purchased by Acadian Seaplants Ltd (also see Section 4.5.1). Initially, Acadian Seaplants focused on the carrageenan market, but the company was unable to compete with wild harvesters due to their higher production and labour costs, and various market factors (reviewed in Chopin et al., 1999). In response, Acadian Seaplants Ltd converted their operation to produce a value-added product by manipulating the colour and texture of certain *Chondrus* strains (Figure 13B).

Figure 15 | The world's largest outdoor seaweed cultivation ponds, owned and operated by Acadian Seaplants Ltd, which cultures Irish moss (*Chondrus crispus*) in Charlesville, Nova Scotia, (Acadian Seaplants Ltd).

In summary, the commercial-scale aquaculture of *Chondrus* was largely pioneered in Atlantic Canada and is primarily land-based. It incurs very high start-up and daily operational costs and requires complex production facilities. Consequently, the industry is yet to expand significantly beyond Atlantic Canada.

7.2.4. Open-water culture of Chondrus

While *Chondrus* aquaculture is primarily land-based, there are a few cases where it has been cultured in open water. Chopin et al. (1999) collected wild specimens from Basin Head, Prince Edward Island, and transplanted them inside mesh bags for grow out in other areas across the province. They reported daily summer growth rates of 3 – 4 %, suggesting that transplanting wild specimens for commercial grow-out has some potential. Similarly, Zertuche-González et al. (2001) transplanted wild specimens from Maine, USA, to Baja California, Mexico, which is outside its natural distribution. The authors planted *Chondrus* inside vertical mesh bags (similar to mussel socks) which were hung from a traditional longline system. Overall, growth rates were much lower than the study in Prince Edward Island, averaging at 1.3 % per day.

7.2.5. Opportunities and barriers

Although Acadian Seaplants Ltd has experienced incredible success culturing *Chondrus* in their land-based facility in Nova Scotia (see Section 7.2.3), there are presently very few opportunities for further expansion of this industry. This is because the intricate production and processing methods the company uses, and the niche markets they access, are the result of over six decades of research and development. Consequently, it would be very difficult for a new company to enter the industry and produce *Chondrus* at a scale that is profitable and competitive. In addition, the commercial open water culture of this species has not been achieved elsewhere, and consequently, there are no established methods or best practices to help guide prospective growers. Therefore, it would be incredibly challenging to pioneer the open water culture of *Chondrus*, especially considering its complex life cycle (see Section 7.2.2).

7.3. Dulse, *Palmaria palmata* (red seaweed)

Palmaria palmata, commonly known as dulse, is a perennial red seaweed (Figure 16) that is rich in proteins, minerals, and vitamins (see Table 2). It has a long history of being wild harvested, dried, and eaten in North America and Europe (Grote, 2019). In the Northwest Atlantic, wild commercial harvests still occur within the Bay of Fundy and Gulf of Maine. Once harvested, it is typically sundried for 8 hours, weighed, and then packaged, but it may also be ground into powders and flakes (Chopin and Ugarte, 2006).

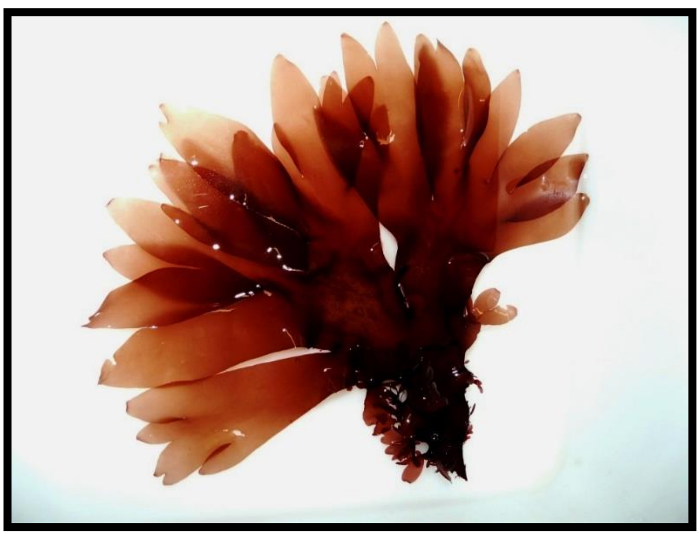

Figure 16 | Dulse (*Palmaria palmata*) is a red seaweed that is wild harvested in Nova Scotia (Merinov).

7.3.1. Biology

Palmaria fronds are leathery and variable in shape and colour, usually forming flat foliose blades that are deep red to purple in colour, measuring between 30 – 100 cm in length, and 3 – 8 cm in width. It is commonly found in the intertidal and subtidal zones along the shores of the Maritime provinces, but is particularly abundant in the Bay of Fundy, where it grows in areas of moderate currents and wave exposure (Chopin and Ugarte, 2006; Grote, 2019). Generally, *Palmaria* exhibits optimum growth when attached to cobbles approximately 20 cm in diameter, and on beaches where there is enough water movement to seasonally turn the cobbles over. These types of beaches are most common along the southern half of the Bay of Fundy. *Palmaria* can also grow on the stipes of kelp (Herb Vandermulen, *pers. comm*, November 2022).

Palmaria has an unusual life cycle (Figure 17) as it alternates between a sexual gametophyte stage and an asexual tetrasporophyte stage (reviewed in Van der Meer and Todd, 1980; Werner and Dring, 2011; Grote, 2019; Dumay et al., 2022). *Palmaria* also exhibits extreme sexual dimorphism as the tetrasporophytes and male gametophytes are large and conspicuous, while the female gametophyte is microscopic and encrusting. Thus, commercially harvested specimens only consist of tetrasporophytes and male gametophytes. As female gametophytes are microscopic, *Palmaria* was once thought to only be capable of asexual reproduction. However, its life cycle is now well understood and consists of two key stages:

1. **Sexual phase.** The large male gametophyte releases spermatia which fertilizes the microscopic female gametophyte. The sori of the male appears as milky or translucent bumps. A sporophyte then develops on top of the female gametophyte. Female gametophytes die after a few days if they are not fertilized.

2. **Asexual phase.** The sporophyte then develops into a large tetrasporophyte which becomes sexually mature after about a year. The fronds then develop tetrasporangial sori, which appear as elevated, dark red, irregularly shaped bumps. The non-motile tetraspores are then released and settle on to substrate where they develop into either microscopic female gametophytes (which become sexually mature after several days) or into male sporelings (which develop into male gametophytes, and reach sexual maturity after 9 – 12 months).

7.3.2. Cultivation methods

Palmaria cultivation has been achieved in several countries using a variety of techniques (for comprehensive reviews see Werner and Dring, 2011; Grote, 2019; Dumay et al., 2022). Establishing a hatchery typically begins with the harvesting of wild tetrasporophytes, from which clean fronds with mature sori are selected. These fronds are then placed in tanks directly on top of seed nets or seed string. It is estimated that around 1 kg wet weight of material can provide sufficient spore material to seed 20 m of line. Spore release is then stimulated by lowering the water temperature to 10°C and reducing light to 5 – 10 µmol photons m^{-2} s^{-1}. Initially, light levels are kept low until the male sporelings develop into young gametophytes with fronds.

For land-based aquaculture, the young gametophytes are then moved to larger indoor or outdoor tanks. Light is then increased to 125 – 600 µmol photons m^{-2} s^{-1} depending on the set up, and water temperatures are kept at around 10 °C. The addition of nutrients (e.g., nitrogen, phosphorous, iron, and cobalt) and carbon dioxide can be required. For open water aquaculture, the seeded string or nets are transferred to grow out sites once the young gametophytes have matured for approximately two weeks. Methods vary but longline systems and net bags have shown to be successful. Water currents should ideally be between 5 – 10 cm s^{-1} and temperatures between 6 – 17 °C. Fronds may deteriorate and develop high epiphyte loads during the summer, therefore, deployment in the fall or winter is usually considered optimum. Multiple harvests throughout the season may be possible if growth rates are high enough.

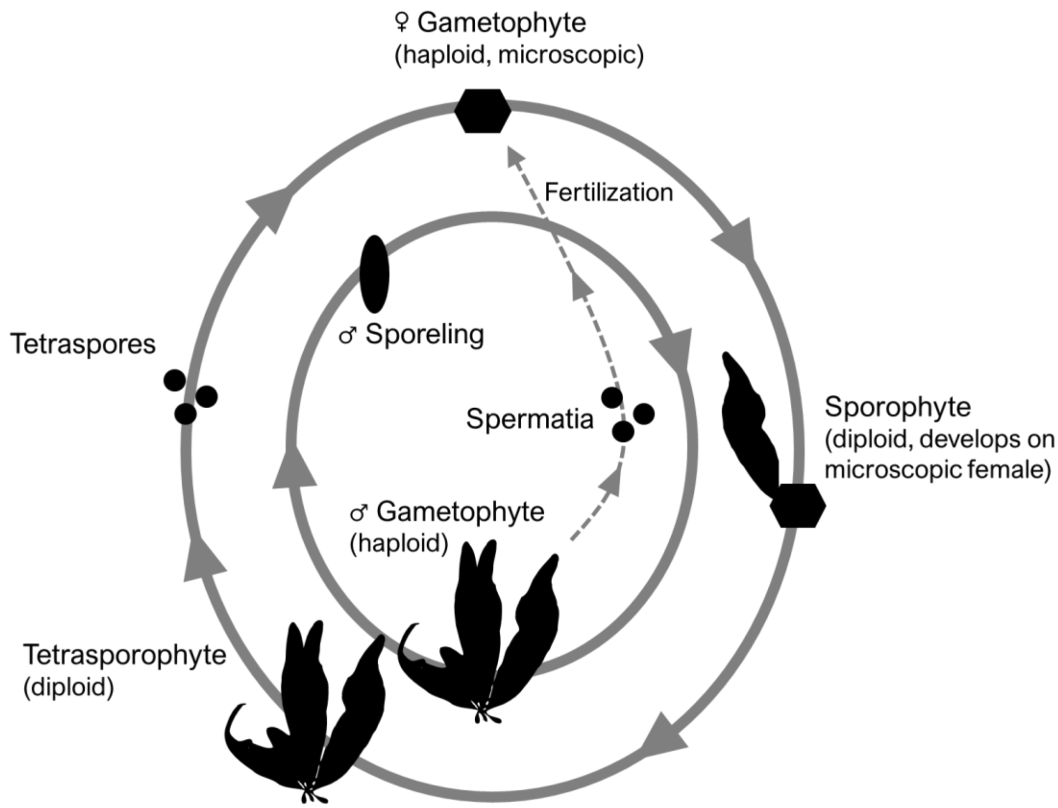

Figure 17 | The simplified life cycle of dulse (*Palmaria palmata*).

7.3.3. Opportunities and barriers

There are some clear opportunities for the development of *Palmaria* aquaculture in Nova Scotia. Firstly, *Palmaria* is widely considered to be healthy and nutritious, and is already a common snack and cooking ingredient in Eastern Canada. Secondly, it is rich in bioactives (see Section 5.1.2) which have potential uses in the nutraceutical and cosmetics industries (reviewed in Werner and Dring, 2011; Grote, 2019). Thirdly, the life cycle of *Palmaria* is well understood, and a number of research efforts have successfully cultivated it in land-based and open water systems (for comprehensive reviews see Werner and Dring, 2011; Grote, 2019; Dumay et al., 2022).

However, if *Palmaria* aquaculture was developed in Nova Scotia, it would have to compete with wild harvesters throughout the Bay of Fundy and Gulf of Maine. It is unlikely that such an industry could compete with wild harvests as the latter does not require a harvesting licence in Nova Scotia, nor does its harvesting or drying require any specialized equipment. In contrast, land-based and open-water culture systems will be substantially more expensive in terms of start-up costs, daily operational costs, labour, and time. Nonetheless, *Palmaria* aquaculture could be advantageous over wild harvests if the industry could create a value-added product. For instance, if the cultured *Palmaria* was more appealing to consumers, or if it contained higher and more consistent yields of nutrients and bioactives, or if consumer demand was to exceed what wild populations could supply.

7.4. Nori / laver, *Pyropia* and *Porphyra* spp. (red seaweeds)

Seaweeds within the genera *Pyropia* and *Porphyra*, commonly known as nori or laver, encompass hundreds of different red seaweeds that are either very difficult or impossible to visually distinguish between. Collectively, they form the most economically valuable group of cultured seaweeds in the world. This is because they have substantial importance in Asian cooking (see Section 2.1). There is also commercial interest in using them in agricultural- and aquafeeds because of their high protein and unsaturated fatty acid content, and for bioremediation of wastewater and IMTA systems, due to their high uptake rates of inorganic nutrients such as nitrogen and phosphorus.

7.4.1. Biology

Nori produces very thin blades between 1 – 2 cells in thickness (Figure 18). Multiple species occur along the intertidal zones of the New England and Eastern Canadian coast. Life histories are very complex and vary between species as some are perennial while others are annual. Likewise some species have separate male and female gametophytes while others are hermaphroditic. Generally, nori exhibits alternating generations between a conspicuous gametophyte stage and a microscopic filamentous sporophyte stage, known as the 'conchocelis' phase. The conchocelis phase bores into oyster shells, and upon maturation, releases 'conchospores', which grow and develop blades (also see Section 2.1). Nori also has multiple strategies of asexual reproduction, often involving spores that can grow into conchocelis or gametophytes.

Figure 18 | *Porphyra umbilicalis* is a species of nori (WikiCommons)

7.4.2. Traditional open-water cultivation methods in Asia

Pyropia yezoensis and *P. haitanensis* are the two major species of nori cultivated in Asia. As briefly discussed in Section 2.1, there are four key stages in its cultivation:

1. **Cultivation of conchocelis stage.** In spring (March / April), wild or cultivated nori blades are dried and resubmerged in seawater (around 23 °C) to stimulate the release of 'zygotospores'. Typically, this is conducted inside land-based tanks stocked with sterile mollusc or artificial shells. The spores are immotile and quickly settle on the shells. Low light conditions (25 – 50 µmol photons m^{-2} s^{-1}) are then used to promote vegetative growth.

2. **Seeding of nets with conchospores.** In the fall, conchospore release is stimulated by stirring or aerating the water and lowering the temperature to 18 – 20 °C. As conchospores are buoyant, nets are seeded by either using a rotary wheel to rotate nets through the surface of the water, or by suspending nets on the surface of the water and spraying them with conchospores.

3. **Nursery rearing of seeded nets and outplanting.** Seeded nets are transferred to shallow, sheltered open water nurseries. Nets are raised out of the water daily to prevent epiphytes and fouling. Once blades are greater than 20 mm, the nets are either outplanted to farm sites, or dried

to 20 % of their water content and frozen for outplanting at a later date. Nets may be suspended at farms using floating / semi floating rafts or between fixed poles (Yarish et al., 2005).

4. **Periodic harvesting of mature blades.** After 40 – 50 days, blades typically reach 15 – 30 cm in size and are then harvested for the first time. They are then harvested again after another 15 – 30 days, and potentially several more times in a single season depending on growth rates.

7.4.3. Other examples of nori aquaculture

Since the 1980's, there have been several experimental trials aimed at culturing nori in open water in Washington State, Alaska, Maine, and New Brunswick (reviewed in Kim et al., 2019). These trials have experienced mixed success, and none appear to have generated any subsequent interest or investment. There is also a reported case where the conchospores of several *Porphyra* species were successfully cultured in outdoor tanks in Israel (Israel et al., 2006). In this case, growth rates generally exceeded those reported for open water by 37 to 480 %, indicating strong potential for this industry. However, it appears no further work has been conducted. Finally, the 'New England seaweed culture handbook' by Redmond et al. (2014) describes in detail some of the processes involved in initiating a land-based aquaculture system for nori. To the best of our knowledge, these methods are yet to be adopted by a commercial operation.

7.4.4. Opportunities and barriers

Nori is a highly valued edible seaweed and an essential ingredient in sushi and other Asian cuisine. Although locally produced nori could potentially supply Asian restaurants and stores in North America and further afield, it would need to compete with nori produced and processed in Japan, China, and Korea which is high quality and inexpensive to import. In addition, open water nori aquaculture has experienced mixed success in North America. Consequently, more research and development are required to aid the development and selection of optimum strains, growing conditions, and production methods. Lastly, while there is potential to extract carrageenan, agar, pectin, and cellulose from nori (Wahlström et al., 2018; Zhao et al., 2019), it is not commonly used for these purposes. Consequently, substantial research and development into processing methods and markets would be required.

7.5. Sea lettuce, *Ulva* spp. (green seaweed)

Green seaweeds within the genus *Ulva* are commonly known as sea lettuce. Some species, like *Ulva lactuca*, are flattened and leaf-like in appearance (Figure 19A), while other species, like *Ulva intestinalis*, are comprised of long, thin fronds (Figure 19B). They are highly nutritious and can be especially rich in carbohydrates, proteins, vitamins, and minerals (also see Table 2), as well as a large diversity of bioactive compounds (reviewed in Dominguez and Loret, 2019). As they can provide a deep umami and brine flavour to foods, *Ulva* is widely used in Asia as a garnish or seasoning, and as an ingredient in salads and soups[19]. They can also be used in fertilizers, feeds for agriculture and aquaculture, and their hydrocolloids can form thermo-reversible gels, similar to agar, carrageenan, and alginate (also see Section 5.2). Consequently, they have many potential commercial applications, particularly in the pharmaceutical, nutraceutical and cosmetic industries (reviewed in Bolton et al., 2009; Bolton et al., 2016; Steinhagen et al., 2022).

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[19] *Ulva* is known as 'aonori' in Japan, 'sea cabbage' in China, and 'parae' in Korea.

Figure 19 | (A) *Ulva lactuca* and (B) *Ulva intestinalis*. Wiki Commons.

7.5.1. Biology

The life cycle of *Ulva* is similar to kelp (see Section 7.1.2) except that both its sporophyte and gametophyte stages are large, conspicuous, and physically similar in appearance (reviewed in Balar and Mantri, 2020). The male and female gametophytes release haploid gametes (Figure 20). Once fertilized, the zygote then develops into a diploid sporophyte which goes on to release male and female zoospores which develop into gametophytes. It is also highly common for fragments of tissue to break off and form cloned individuals. Generally, *Ulva* is considered to be perennial as it tends to die back to small tissue fragments in the winter, from which it regrows during the spring / summer.

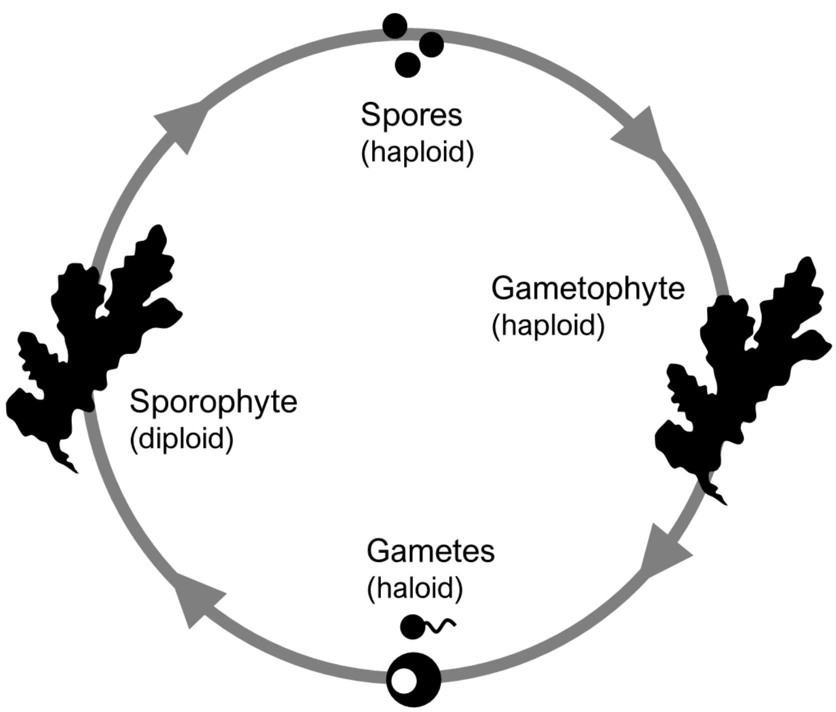

Figure 20 | The simplified life cycle of a sea lettuce (*Ulva* spp.).

7.5.2. Ulva aquaculture

Although green seaweeds contribute less than 0.1% of total seaweed aquaculture production (see Section 3.1), there is substantial interest in developing and expanding the aquaculture of *Ulva* species. This interest is due to its many potential commercial applications, rapid growth and proliferation, ability to grow unattached to substrates, tolerance to high stocking densities, and good survival and growth in wide a variety of temperatures, salinities, and nutrient concentrations (reviewed in Steinhagen et al., 2022).

South Africa is currently the world's largest producer of cultured *Ulva* (see Section 3.1) and is the country's primary species of cultured seaweed (Madibana et al., 2017). There are approximately five farms engaged in *Ulva* aquaculture in South Africa, which collectively produce around 2000 tons a year in shallow raceway ponds (reviewed in Bolton et al., 2009; Msuya et al., 2022). Interestingly, *Ulva* is only co-cultured with abalone (*Haliotis midae*), a highly valuable, edible marine snail that feeds by catching and eating pieces of seaweed drifting in the water column. Thus, rather than selling it, almost all the *Ulva* is fed to the abalone in combination with formulated feed pellets. In addition to providing food, the seaweed removes ammonium and other wastes from the effluent, reducing the quantity of seawater that needs to be pumped in and out into the system, ultimately lowering operating costs. While it is unclear where the cultured *Ulva* originates from, it is most likely that the *Ulva* are harvested from the wild and then vegetatively propagated.

Ulva has also been cultured in multiple countries throughout the world in small-scale, land-based experimental systems, some of which are also IMTA systems (reviewed in Bolton et al., 2009; Bolton et al., 2016; Steinhagen et al., 2022). Recently, Steinhagen et al. (2021) successfully developed an *Ulva* hatchery (Figure 21A) in Sweden (specifically, *U. fenestrata*) and then outplanted the seeded lines to open water longlines (Figure 21B). As the nutrient and biochemical composition of *Ulva* can be strongly influenced by environmental conditions and life stage (i.e., gametophyte vs. sporophyte), it has been argued that using such land-based hatcheries will result in more consistent yield of nutrients and commercially important biochemical compounds (Steinhagen et al., 2022), and that growing *Ulva* in land-based systems throughout its life cycle could further improve this (Zertuche-González et al., 2021).

7.5.3. Opportunities and barriers

Presently there are more barriers than opportunities for *Ulva* aquaculture in Nova Scotia. Firstly, while its bioactives and gel-forming properties have many potential uses, its commercial applications are untested and remains an active area of research and development. Secondly, although *Ulva* is widely eaten in Asia, the extent of consumer demand in Europe and North America is unknown. Thirdly, and perhaps most importantly, *Ulva* are widely considered to be a nuisance species. This is because there are hundreds of accounts from around the world where *Ulva* has reached excessively high biomasses and subsequently washed ashore in large quantities (Joniver et al., 2021). Known as 'green tides', such *Ulva* blooms primarily occur in polluted, eutrophic waters, where they can negatively impact coastlines and intertidal shellfish fisheries, and lead to anoxic waters / sediments and unpleasant smells.

One of the largest green tide events occurred during the Olympic sailing games in China in 2008. In response, the Chinese Government spent $100 million dollars to hire 10,000 people who collectively removed more than one million tons of *Ulva* from the shoreline. These blooms now occur annually and are widely believed to be the result of elevated nutrient levels caused by agriculture and other industrial activities (Rybak and Gąbka, 2018). Some evidence has also linked the blooms to regions where nori aquaculture is highly active (Zhang et al., 2017). Such green tides have also been reported in Prince Edward Island and Passamaquoddy Bay, New Brunswick (Raymond et al., 2002; Robinson et al., 2005).

Figure 21 | (A) Lines seeded with *Ulva* which were then (B) outplanted on to long lines in Sweden (Sophie Steinhagen, University of Gothenberg, Tjärnö Marine Laboratory).

As *Ulva* has the potential to spread, proliferate, colonise surfaces, and cause environmental damage, it is unlikely that its open water culture would gain public and government support in Nova Scotia. Thus, prospective growers may want to consider land-based production systems which have substantially less risk of contaminating the coastal environment. However, these systems are associated with higher start-up and operational costs. If the commercial land-based production of *Ulva* can be realized, the production of a value-added product could help negate these costs.

7.6. Cultivated seaweed workshop: Halifax, Nova Scotia

In October 2022, the Aquaculture Association of Nova Scotia (AANS), Centre for Marine Applied Research (CMAR), and Ecology Action Centre (EAC), jointly held a workshop in Halifax, Nova Scotia for stakeholders interested in seaweed aquaculture. Over 60 delegates attended the event, representing a wide variety of backgrounds, including funders / investors, government regulators, non-governmental organizations, scientists, fishermen, chefs, and nutritionists. Thus, it is clear there is substantial interest in further developing the seaweed aquaculture industry in Nova Scotia. As part of the workshop, an interactive discussion was held on the strengths, weaknesses, and opportunities of the industry, which was divided into three themes: (1) post harvesting, processing, and marketing; (2) regulations and policy; and (3) research and support. The main points raised from these discussions are summarized below.

7.6.1. Post harvesting, processing, and marketing

The lack of seaweed processing facilities in Nova Scotia[20], coupled with unknown market demand and access, was widely identified to be the primary barrier facing the expansion of seaweed aquaculture in Nova Scotia (also see Section 7.1.7). This issue is cyclical in nature (Figure 22) for multiple reasons. Firstly, depending on the product, seaweed processing can be highly complex, requiring specialized equipment and methods that are specific to certain industries and markets. Therefore, the end markets and industries must be identified before a processing facility is established. However, it is unknown which markets have potential in Nova Scotia, and whether more technologically advanced facilities (e.g., for various seaweed extracts) could be competitive on a national and international level. As a result, investors may be deterred from investing in a processing facility which targets such untested markets. Secondly, for a processing facility to be profitable, it would probably require a large and constant supply of raw product. Presently, wild[21] and cultured harvests in Nova Scotia may be too small and seasonal to be economically sustainable but could potentially be overcome by importing seaweeds from other provinces and countries. Despite these problems, seaweed processing for human consumption and agricultural applications can be relatively simple. However, it is unknown how much consumer demand exists for these types of seaweed products, and it will likely take considerable education and outreach efforts to inform consumers of the benefits of using seaweed and slowly change their perception on seaweed products.

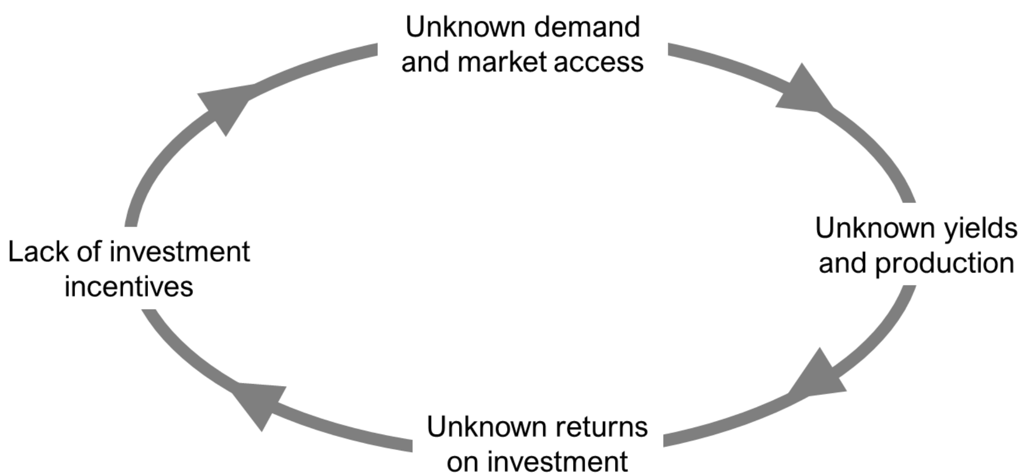

Figure 22 | The cyclical barriers to seaweed processing in Nova Scotia.

Overall, the business model for processing and marketing seaweeds in Nova Scotia remains unclear and untested. However, one of the strengths identified during the workshop is that Nova Scotia already has substantial infrastructure for exporting seafood products to USA, Asia, and other parts of the world including other Canadian provinces. Another strength was that Nova Scotia encompasses multiple federal, provincial, private, and academic research organizations that specialize in food and food processing science. Consequently, Nova Scotia has the capacity to overcome these barriers.

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[20] There are, however, several processing facilities for wild harvested rockweed in Nova Scotia.
[21] Kelps are not permitted for wild harvest in Nova Scotia.

7.6.2. Regulations and policy
Seaweed aquaculture is widely considered to be the most environmentally benign form of aquaculture (see Section 6). However, in Nova Scotia, it is currently subjected to the same licencing and leasing processes as shellfish aquaculture. Consequently, some stakeholders felt these regulations are too stringent, and disproportionally time-and cost-expensive (particularly regarding the requirement to submit a development plan) relative to its potential environmental impacts. In addition, several stakeholders claimed the licencing and leasing process takes over 2 –3 years and is prone to stalling for undetermined lengths of time. Added to this, growers are unlikely to get revenues for 3 – 4 years on the costs incurred before production begins, and they will not get a return on their investment for 4 – 6 years (Gardner Pinfold Consultants, 2022). Nevertheless, the Government of Nova Scotia is currently conducting a comprehensive review of existing aquaculture regulations, which includes substantial stakeholder engagement and public consultation. Thus, some of these regulatory issues may be addressed and resolved in the near future.

7.6.3. Research and support
Research and support were largely seen as a strength in Nova Scotia due to substantial research capabilities within the province. However, some stakeholders argued the case that greater educational and awareness tools for prospective growers are needed, particularly for fishermen who may be interested in expanding into seaweed aquaculture but may not have the time and resources to navigate the regulatory process and learn about the production methods and potential markets.

8. Regulations and management of seaweed aquaculture in Nova Scotia

In Nova Scotia, aquaculture operations are subject to comprehensive regulatory and management processes, which vary depending on the aquaculture operation. This section aims to guide prospective and established seaweed growers, as well as seaweed processors, through these regulatory processes, from the initial application to subsequent reporting and monitoring.

8.1. Key aquaculture regulations in Nova Scotia

NSDFA is the lead regulator and manager of aquaculture in Nova Scotia. The *Fisheries and Coastal Resources Act* (S.N.S. 1996) and its regulations, including the *Aquaculture Licensing and Leasing Regulations* (N.S. Reg. 347/2015) and *Aquaculture Management Regulations* (N.S. Reg. 348/2015), are the primary legislation governing aquaculture within the province. Aquaculture is also subject to federal regulation under the federal *Fisheries Act* (R.S.C. 1985), the pending federal Aquaculture Act (expected to be finalized in 2023), the *Canadian Navigable Waters Act* (R.S.C. 1985), and many other interrelated pieces of legislation (reviewed in Raymond et al., 2002; Howarth et al., 2022).

8.2. Acquiring an aquaculture licence and lease

All open-water aquaculture sites in Canada require a valid lease and licence. Leases entitle the owner / operator to install and use aquaculture gear in a specified area, while licences entitle the owner / operator to stock the facility, subject to conditions specified within the licence. To acquire or amend a licence and lease, an application must be submitted to NSDFA. Depending on the application, NSDFA will then follow either an 'administrative' (See Section 8.2.1) or 'adjudicative' (see Section 8.2.3) process to decide whether the application is approved, approved with conditions, or rejected (reviewed in Nova Scotia Department of Fisheries and Aquaculture, 2022).

8.2.1. Administrative process

The administrative decision process is relatively streamlined and is overseen by the 'Aquaculture Administrator', an appointed employee of NSDFA (Nova Scotia Department of Fisheries and Aquaculture, 2021b). It covers applications listed in Table 3 and can be divided into three phases:

- **Phase 1 – Pre-application.** The proponent initiates a pre-application discussion with NSDFA to determine what information and data are needed for Phase 2.
- **Phase 2 – Review.** The proponent submits an application form and development plan (see Section 8.2.5). Comments received from internal reviewers and relevant network partners (see Section 8.2.6) are compiled. The application is then opened for public comment for a period of 30 days.
- **Phase 3 – Administrator decision.** The Administrator makes a final decision based on the development plan and all comments and recommendations received, which is then published on NSDFA's website.

Table 3 | The types of aquaculture applications that undergo an administrative decision process.

Land-based operations
• New land-based licences; • New experimental land-based licences; • Renewals of existing land-based licences; and • Amendments to existing land-based licences.
Marine-based operations
• New experimental marine licences and leases (see Section 8.2.2); • Renewals of existing marine licences and leases; • Reallocation of existing marine licences and leases; • Boundary amendments that do not result in expansion of the site; • Amendments to gear or cultured species (non- finfish species only); and • New marine licences and leases within ADAs (see Section 4.5.3).

8.2.2. Experimental licences and leases

Applying for experimental licences and leases follows the administrative process described above, and is therefore a relatively streamlined process. Thus, it may be a great option for prospective seaweed growers to determine if partial production is feasible in a certain area, and to test different gear types, configurations, and production methods (reviewed in Nova Scotia Department of Fisheries and Aquaculture, 2020b). As experimental licences and leases can be renewed annually for up to five years, it provides an extended opportunity to collect any data (e.g., oceanographic) required for a full application, or to trial aquaculture to ensure location viability. These sites are not intended to be commercial farms, and there are restrictions on how cultured biomass may be used. To apply for an experimental licence and lease, the proponent must submit a development plan (see Section 8.2.5) to NSDFA which demonstrates that the aquaculture operation will:

- Test or develop new technology or methods; and / or
- Carry out basic research; and / or
- Test the technical feasibility of the site; and
- Not be on a scale that exceeds what is needed for experimental purposes.

8.2.3. Adjudicative decision process

The adjudicative decision process is overseen by the independent Nova Scotia Aquaculture Review Board (Nova Scotia Department of Fisheries and Aquaculture, 2021a). It covers application types listed in Table 4 and is divided into three phases:

- **Phase 1 – Scoping:** The proponent submits a proposal for an 'option to lease' in an area they would like to evaluate for potential aquaculture development. NSDFA then decide whether to approve the request to explore the location. If approved, the proponent has six months to examine the area and submit a business plan and formal application (i.e., the 'option period', which can be extended by another six months if requested and approved). Prior to phase 2, there are requirements for at least one stakeholder engagement event.

- **Phase 2 – Review:** The proponent submits an application form, a development plan (see Section 8.2.5), and a scoping report which includes results from stakeholder engagement. NSDFA may request more information, and the application is shared with network partners (see Section 8.2.6). NSDFA then submit the application to the Nova Scotia Aquaculture Review Board.

- **Phase 3 – Board decision:** The Aquaculture Review Board holds a public hearing at a community near to the proposed site. Members of the public can submit written comments, request to speak at a hearing, and / or can apply to be an intervenor[22] at the hearing. The Board then has 30 days to make their decision which is posted publicly on the websites of the Review Board and NSDFA. This decision can be appealed up to 30 days after the announcement.

Table 4 | The types of aquaculture applications that undergo an adjudicative decision process.

Decisions made by the Aquaculture Review Board
• New marine licences and leases; • Amendments to expand existing marine licences and leases; and • Amendments to add finfish species to existing marine licences and leases.

8.2.4. Licensing a seaweed hatchery

In Nova Scotia, land-based seaweed hatcheries must be licensed by NSDFA as a land-based aquaculture site. Educational facilities (i.e. universities) can obtain an Institutional License for the production of seeded

[22] The Nova Scotia Aquaculture Review Board must grant intervenor status to any person requesting it who, in the opinion of the Board, is substantially and directly affected by the aquaculture proposal.

lines that are carrying out research activities that are not for commercial gain (see Section 55A of the *Fisheries and Coastal Resources Act*).

8.2.5. Development plan

Most aquaculture license and lease applications to NSDFA (e.g., finfish, shellfish, marine plant, land-based, marine-based, and experimental) require a development plan (see Nova Scotia Department of Fisheries and Aquaculture, 2020b; Nova Scotia Department of Fisheries and Aquaculture, 2020c; Nova Scotia Department of Fisheries and Aquaculture, 2020d; Nova Scotia Department of Fisheries and Aquaculture, 2020e). These generally require information on: production plans (e.g., gears, densities, strain); infrastructure, services and suppliers; employment; financial viability; results obtained from baseline monitoring; oceanographic and biophysical characteristics of the site; and any expected impacts, benefits and proposed mitigation regarding local communities, wild salmon, water navigation, recreational users, fisheries, and the province as a whole.

8.2.6. Network partners

Regardless of which decision process is undertaken, all aquaculture applications and development plans are reviewed by NSDFA and network partners. Network partners consist of provincial and federal departments that have regulatory jurisdiction over certain aspects of aquaculture. This may involve several groups within DFO, including the Fish and Fish Habitat Protection Program, Aquaculture Management, the Marine Planning and Conservation program, DFO Science, and various fishery departments. Other federal departments like Environment and Climate Change Canada (ECCC), Transport Canada, and the Canadian Food Inspection Agency (CFIA) may also be involved in the process. Provincial partners may include the Department of Agriculture, Communities, Culture, Tourism, and Heritage (CCTH), Natural Resources and Renewables, and Nova Scotia Environment. Together, NSDFA and network partners evaluate the potential environmental and socio-economic impacts of aquaculture applications based on published scientific research, any newly collected physical and ecological data, and public engagement.

8.2.7. Farm Management Plan

All aquaculture licence holders in Nova Scotia are required to prepare a Farm Management Plan (FMP) prior to stocking their site (Nova Scotia Department of Fisheries and Aquaculture, 2020a). For marine plants, the FMP must include detailed information and procedures on marine plant health management, environmental monitoring, and farm operations such as noise management, retrieval of loose gear, maintaining the site in good order, and managing interactions with wildlife. NSDFA has established minimum compliance requirements for the procedures contained within an FMP, and have created FMP templates for proponents to use if they wish (see Nova Scotia Department of Fisheries and Aquaculture, 2020a).

8.3. Baseline and annual monitoring

All marine aquaculture applications intending to establish a new lease (including experimental), reactivate a lease, or amend the boundaries of an existing lease, must undergo baseline monitoring according to the 'Environmental Monitoring Program (EMP) framework for marine aquaculture in Nova Scotia' (Nova Scotia Department of Fisheries and Aquaculture, 2021c) and detailed in the 'Standard operating procedures for baseline monitoring of marine shellfish aquaculture in Nova Scotia' (Nova Scotia Department of Fisheries and Aquaculture, 2021d). Although not explicitly mentioned, an aquaculture application to culture nothing but seaweed would have to comply with these baseline monitoring procedures, which primarily involves obtaining video footage of the seabed (Danielle St Louis, NSDFA, pers. comms, August 2022). Any marine applications that intend to culture finfish at any stocking density must also undergo annual monitoring, which requires the collection and analysis of benthic videos and sediment samples (Nova Scotia Department of Fisheries and Aquaculture, 2021d). NSDFA may also require annual monitoring of other aquaculture sites (including shellfish and marine plants) as they deem fit.

8.4. Ongoing regulatory review

The Government of Nova Scotia is currently conducting a comprehensive review of existing aquaculture regulations. Therefore, these licencing and leasing processes could potentially change in the near future.

8.5. Harvesting and reintroducing wild seaweed material

Most form of seaweed aquaculture require periodic harvesting of wild sorus tissue. The harvesting of wild marine plants attached to substrates requires a marine plant harvest license. If wild harvesting is to take place within the Bay of Fundy, which includes St Mary's Bay (Figure 23), approval must be obtained from NSDFA. Otherwise, the licence must be obtained from either DFO Maritimes or Gulf regions (see here for contact information). Typically, all marine plant harvest licences stipulate that the holdfasts must be left intact (i.e., only the blades of the seaweed can be cut). A licence is not required to take free-floating marine plants that have naturally become detached (Edward Parker, DFO, pers. comms, August 2022).

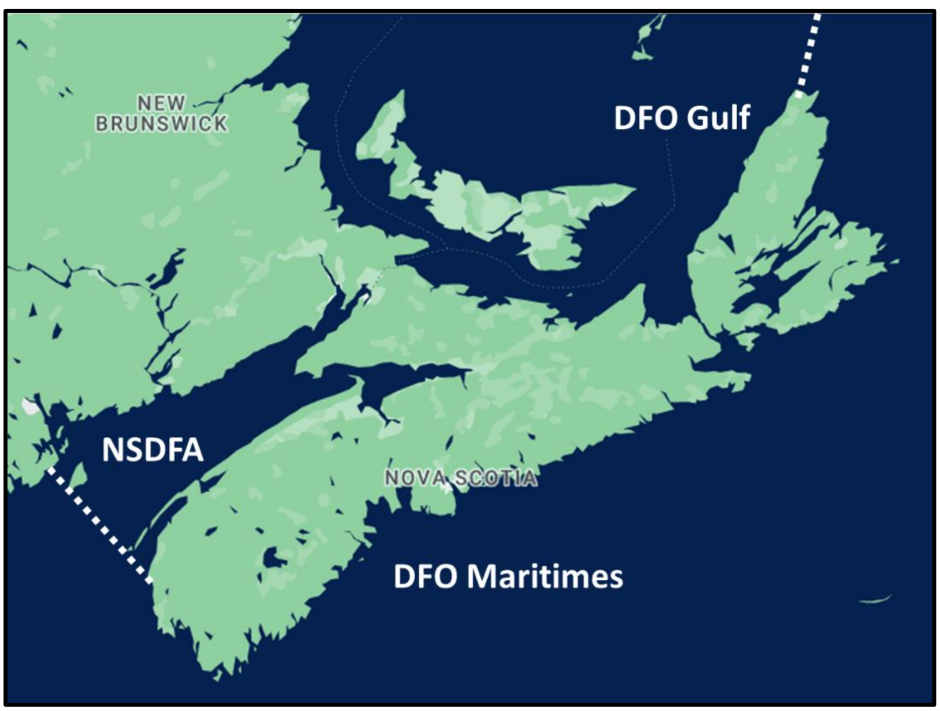

Figure 23 | Map showing the three different regulators, and their respective jurisdictions, for granting marine plant licences in Nova Scotia. Such licences are required for the wild collection of sorus material.

Reintroducing seaweeds to the wild (e.g., in the form of seeded lines) is permitted under the aquaculture licence granted by NSDFA. Typically, marine plant aquaculture licenses specify that sorus tissue must be collected from the same general area in which they are going to be replanted. For example, it would be highly unlikely that sorus tissue collected in Richmond County would be permitted to be replanted in any other county. Additionally, as the Bras d'Or Lakes are considered to be an area with a high risk of disease transmission (primarily referring to Multinucleate Sphere Unknown X, or 'MSX disease', which infects oysters), it is almost certain that material from this region would be prohibited from being reintroduced elsewhere and *vice versa* (Nathaniel Feindel, NSDFA, *pers. comms*, September 2022). However, the exact distances from which wild sorus tissue can be collected and replanted is an area of regulatory ambiguity and is currently assessed on a case-by-case basis. Potentially, the project by Merinov and NRC (see Section 7.1.6) may be able to provide insight into the genetic variability of *Saccharina* across the province, which could help guide NSDFA in further developing and refining existing regulations.

The *Aquatic Invasive Species Regulations* (SOR/2015-121), under the Federal *Fisheries Act* (R.S.C., 1985, c. F-14), prohibits the introduction of non-indigenous species into the aquatic environment. Therefore, any seaweed species cultured in open water must be endemic to the region, and the seaweed must be free of non-indigenous epiphytes. There is currently no regulatory tool within DFO to approve a non-indigenous species introduction (Edward Parker, DFO, pers. comms, August 2022).

8.6. Seaweed processing licencing

8.6.1. Provincial licencing

In Nova Scotia, most forms of seafood processing require a processing licence from NSDFA. Processing activities requiring a licence include cleaning, cutting, chilling, drying, milling, cooking, canning, freezing, concentrating, smoking, salting, packaging, labelling, and generally preparing seafood products for the market in any manner.

Processing licences differentiate between wild and cultured specimens, and facilities must be licensed for both should they intend to process seafood from either source. However, as there is currently a suspension on the issuance of new seafood processing licences for wild organisms (see Section 8.4), a new license in Nova Scotia can only be issued for the processing of cultured seaweeds, or secondary processing (e.g., of rockweed). There is also the opportunity for seafood processor licence holders to add cultured marine plants to their existing licence by contacting the Licensing and Registration Unit within NSDFA (Robert Ceschuiutti, NSDFA, *pers. comms*, October 2022). Under the terms of a processor licence that includes marine plant species, the annual reporting of the following information is required:

- The origin and initial form of each seaweed species processed.
- The volume of each seaweed species processed.
- The processing method.
- The jurisdiction to which the seaweed is exported.

Overall, the provincial licencing of seaweed processors is a relatively new requirement in Nova Scotia and, as a result, there remains some ambiguity in which situations a licence is required, particularly regarding how far along the supply chain a licence is required. For instance, if a company purchased fresh seaweed, which they dried and milled into a powder, they would likely require both a buyer and processor licence. If they then sold that powder to a second company, which adapted the powder into a seasoning blend, and then sold to another company for packaging and export, it is likely that both these companies would require secondary processing licences. But this is far from certain. Furthermore, the requirement of a provincial license for seaweed processing is unique to companies based in Nova Scotia, as other provinces do not have these additional regulatory measures in place. As part of the ongoing regulatory review in Nova Scotia, NSDFA are presently working on a policy document that will outline their formal position on the licensing of marine plants and is expected to be finalized in 2023.

8.6.2. Federal licencing

In addition to the provincial licence described above, there are many situations where federal licenses are also required. For example, if any of the end-products are intended for human consumption, and these products will be exported across provincial and national boundaries, the processor will need to be federally registered with CFIA, and the processing facility will need to comply with *Safe Food for Canadians Regulations* (SOR/2018-108). Processors can be issued a licence under the *Safe Food for Canadians Regulations* when a 'Preventive Control Plan' has been adequately developed and implemented. This plan outlines a description of the measures taken by the processor to mitigate potential hazards and risks the product may pose to the end consumer. These plans are specific to a product and facility.

Processing seaweeds for non-food use does not require licencing under *Safe Food for Canadians Regulations*, however, the business must comply with other federal regulations and may even require federal approval prior to sale. For example, processing raw materials (including seaweeds) into a 'natural health product' must comply with *Natural Health Product Regulations* (SOR/2003-196). Producers of natural health products require a site licence for all locations where the products are manufactured, packaged, labelled, or imported into. Additionally, each individual product produced within an approved site requires a product licence. A condition of the product licence requires demonstrating that 'Good Manufacturing Practices' are followed.

Seaweeds processed for use as animal feed must comply with *Feed Regulations* (SOR/83-593). Although licencing is not required for manufacturing of feed ingredients, products may require registration with CFIA prior to its approval for sale. Feeds that are exempt from registration must still conform to the standards prescribed in these regulations for packaging and labelling, as well as provide evidence demonstrating the safety and efficacy of the feed. Similarly, seaweeds processed for use as fertilizers or plant supplements must comply with *Fertilizer Regulations* (C.R.C., c. 666). Licencing is not required for facilities involved in the manufacture of fertilizer or plant supplements, however, products may require registration with CFIA, and must comply with the standards for labelling and 'guaranteed analysis'.

8.7. Shellfish aquaculture in waters not monitored and classified by the CSSP

As open water seaweed aquaculture remains a fairly new and untested commercial enterprise in Nova Scotia, some prospective farmers may choose to co-culture seaweeds and shellfish, rather than rely exclusively on seaweed harvests for income. The Canadian Shellfish Sanitation Program (CSSP) is a federal food safety program that ensures the consumption of Canadian shellfish does not negatively impact human health. However, extensive areas of Nova Scotia are 'unclassified' which could act as a barrier for any growers looking to co-culture both shellfish and seaweed in those areas.

The CSSP is jointly administered by CFIA, ECCC, and DFO, and aims to minimize the health risks associated with the consumption of contaminated shellfish, such as oyster and mussels. Under the CSSP, the

Government of Canada organizes the collection of water samples in 'shellfish harvest areas' around Canada. These samples are then analyzed for biotoxins and bacterial contamination and compared to Canadian marine biotoxin and microbiological standards. These harvest areas are then classified as 'approved', 'closed', or 'partially closed' for shellfish harvesting. However, there are extensive areas around Nova Scotia that are not monitored by the CSSP and are 'unclassified', meaning commercial shellfish harvesting is not permitted. Proposals for expansion of CSSP sampling can be submitted in writing to the chairperson of the Regional Interdepartmental Shellfish Committee[23] (RISC). However, it can take between 1 – 4 years after proposal submission for it to be approved or rejected, and subsequent water sampling to occur.

Theoretically, prospective growers could apply and be approved to establish new shellfish farms in unclassified areas, but they would not be allowed to harvest and sell their shellfish. Then again, growers could use leases in unclassified areas for grow out and then move (or 'relay') their stock to areas approved for harvesting, or to land-based depuration facilities. If they are relayed to a "clean" lease, then they have to depurate for three weeks, but growers can reduce this time to one week if they pay to have the testing done themselves (Lewis Clancey, NSDFA, *pers. comm*, December 2022). Shellfish that are relayed in excess of 21 days may be exempt from testing (CFIA, 2018). In contrast, land-based depuration facilities have to first be approved and validated by CFIA and, therefore, do not require subsequent testing providing the minimum depuration time (specific to each facility) has been completed.

9. Summary

Seaweed aquaculture is a multi-billion-dollar global industry which collectively produces more biomass than any other organism cultured within the marine environment. Not only are seaweeds highly nutritious sources of food, but they also have applications in a variety of industries including agriculture, food processing, cosmetics, and pharmaceuticals. Furthermore, seaweed aquaculture is widely considered to be the most environmentally benign form of aquaculture, which may generate more environmental benefits than it does negative impacts.

The seaweed aquaculture industry is still in its infancy in North America, particularly in Eastern Canada and Nova Scotia. Nonetheless, there is significant interest (and potential) in developing and expanding the industry. At present, the seaweed aquaculture industry in Nova Scotia is predominantly interested in culturing sugar kelp (*Saccharina latissima*), and potentially winged kelp (*Alaria esculenta*) and horsetail / oarweed (*Laminaria digitata*). As there are already several kelp operations and hatcheries in existence and in development, there is strong potential for the immediate expansion of the kelp aquaculture industry in Nova Scotia. There are several other species which have commercial potential that could be cultured in Nova Scotian waters. However, competition with wild harvests (*Palmaria palmata*) and with existing producers (*Chondrus crispus*), or the potential for negative environmental impacts (*Ulva* spp.), all pose barriers for these other species. Other than kelp, nori aquaculture probably has the most potential for development, but further research is needed on production methods, markets, and processing.

By far the largest barriers to the seaweed aquaculture industry in Nova Scotia are limited processing capabilities, unclear access to markets, and unknown consumer demand. In addition, many stakeholders

[23] Composed of area / regional DFO, ECCC, and CFIA representatives.

have expressed their frustration with the existing regulatory process as the industry is subject to the same licencing / leasing and baseline monitoring guidelines as shellfish aquaculture, which many proponents feel are disproportionally stringent relative to its potential for environmental impacts.

In summary, the seaweed aquaculture industry has strong potential for growth in Nova Scotia and could expand rapidly in the next 10 – 20 years. However, substantial efforts are required to improve processing capabilities, access to markets, and consumer demand.

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