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The Aquaculture and Market Opportunities for New Zealand Seaweed Species

The red seaweed Asparagopsis armata *which is currently the focus of intense interest for commercial aquaculture development in New Zealand because of its potential to be used as a livestock supplement solution to reduce ruminant methane emissions (Source: NZ Herald)*

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Report Prepared For: The Nature Conservancy

December 2021

Introduction

The aquaculture of seaweeds is a common activity in many parts of the world but has received very little attention in New Zealand. More recently there has been increasing investment and growth of seaweed aquaculture activities in temperate regions of the world, partly driven by the potential environmental benefits of this activity. These benefits include the potential for the capture of excess nutrients in coastal ecosystems, contributing to carbon sequestration, habitat provisioning, as well as supplying food and materials for the use of humankind. Consequently, seaweed aquaculture is increasingly being promoted as a "restorative aquaculture" activity, i.e., defined as the cultivation of seaweed in a manner that generates positive ecological and social impacts. A recent review of the global potential for the development of restorative seaweed aquaculture identified New Zealand as one of the top 25 marine ecoregions based on an assessment of environmental, socioeconomic, and human health factors (Theuerkauf et al., 2019). While seaweed has been harvested from the wild in New Zealand for food and materials since humans first arrived in the country, there has been very limited seaweed aquaculture activity. Currently there are more than 170 coastal marine farms around New Zealand with permits to grow various seaweed species, but at this time there is negligible seaweed production from aquaculture, with the majority of the small amounts of commercially utilised seaweed supplied from either harvest from the wild, including collection of beach cast seaweed, and harvesting biofouling seaweeds from mussel farms (Bradly et al., 2021). To some degree, this lack of development of seaweed aquaculture activity is due to a lack of clarity around the practical and economic opportunities for seaweed aquaculture production in New Zealand. In an effort to promote the development of restorative seaweed aquaculture, The Nature Conservancy has supported this review of the aquaculture and market opportunities for seaweed in New Zealand. To undertake this review an extensive search of readily available scientific and technical literature was carried out using directed scientific literature databases and web searches. In addition, personnel involved in the existing seaweed industry in New Zealand were interviewed to provide further context to this study.

Global Status of Seaweed Aquaculture

The global production of aquatic algae from aquaculture has grown dramatically over the last 30 years to reach 32.4 million tonnes of algae in 2018 (Figure 1, FAO 2020). The global aquaculture production of seaweed has more than tripled in the 20 years between 2000 and 2018, increasing from 10.6 to 32.4 million tonnes.

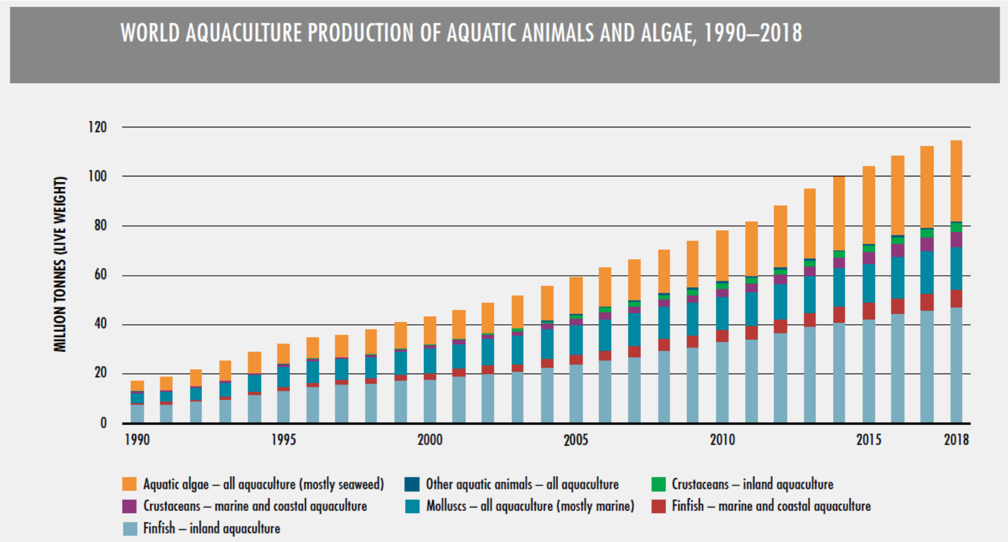

Figure 1. Global production from aquaculture for aquatic animals and algae from 1990 to 2018 (FAO, 2020).

The majority of seaweed aquaculture production is from a small number of countries in Asia, especially China, Indonesia, the Philippines, North and South Korea (FAO, 2020). The world production of seaweed is dominated by the aquaculture of Japanese kelp (*Saccharina japonica*) which is used as a food and a raw material for extracting useful chemical compounds. A group of tropical seaweed species, (especially *Kappaphycus alvarezii* and *Eucheuma* spp.) make up the second major group of cultured seaweeds, which provide the raw materials for extracting carrageenan, a widely used food ingredient and industrial compound. Much of this seaweed aquaculture production is underpinned by low wage-cost economies relying on piecework to maintain production. Traditionally seaweeds are an important component of the cuisine of many Asian countries, especially China, Japan and the Republic of Korea, which have led to the development of seaweed aquaculture for food species. However, seaweeds are also used for a wider range of other purposes including animal feed, fertilizers, pharmaceuticals, cosmetics as well as for a variety of other purposes. In medicine, for example, they are used to treat iodine deficiency and as a vermifuge (i.e., a treatment for parasitic worms). Seaweeds are industrially processed to extract a variety of thickening and gelling agents, such as alginate, agar and carrageenan, which are generally produced in a dried powder form. There is also increasing attention on the nutritional value of a variety of seaweed species, because of their high content of vitamins, minerals, long chain polyunsaturated fatty acids and vegetable proteins. The use of seaweeds for biofuel is also being investigated.

Status of Seaweed Aquaculture in New Zealand

While there is currently strong interest in the aquaculture of seaweed species in New Zealand there are no existing substantial operations and very little history of the activity in the country as a base to build from (Zemke-White et al., 1999). More than 20 years ago there were some pilot-scale intertidal cultures of *Gracilaria* and *Pyropia* species, both of which failed commercially (Dr Eric Terzaghi, pers. comm., Terzaghi et al., 1987). There is currently some commercial use of wakame (*Undaria pinnatifida*) that is harvested from among the biofouling on mussel farms (White & White, 2020). The harvested wakame is sold fresh into local restaurants and to bespoke market outlets, such as natural pet food manufacturers. However, this wild-caught wakame can be less suited for food products than overseas farmed alternatives due to inconsistency of texture and blade form that can be achieved through selective breeding in aquaculture (White & White, 2020). While there has been interest in commercially farming this species, it is exotic to New Zealand and is classified as an "unwanted organism" under the Biosecurity Act 1993. Consequently, any aquaculture of this species is prohibited and its harvesting species is strictly controlled at present. A commercial fishing permit is required, there are strict rules on the transfer and selling, and wakame can only be harvested from man-made surfaces (White & White, 2020). Wakame, giant kelp (*Macrocystis pyrifera*) and common kelp (*Ecklonia radiata*) are the three species of seaweed found in New Zealand with probably the greatest current interest in aquaculture development. The methods for farming both wakame and giant kelp are well developed overseas, as are methods for congener *Ecklonia* species, with them mostly being grown from buoyed lines in shallow coastal waters.

Giant kelp, *Macrocystis pyrifera,* is already available for wild harvest in New Zealand as a recognised commercial fished species, with a total allowable commercial catch of over 1500 t per year, but most of this allocation remains unharvested (MPI 2017). It is one of the world's most fertile and rapidly growing kelp species and is harvested at a small scale in New Zealand for the production of food seasonings and supplements (White & White, 2020). Other seaweed species are harvested in New Zealand in small volumes as beach cast seaweed, including the common kelp and species of *Pterocladia* and/or *Pterocladiella* (Zemke-White et al., 1999). These harvested seaweeds have mostly been used for feeding cultured abalone, stock feed, and for producing agar. Currently, the largest market for locally harvested seaweeds is a single company making soil fertilisers and animal supplements, which mostly utilises beach cast common kelp.

There are estimated to be around 800 native seaweed species in New Zealand, some of which are likely to have the potential for development in aquaculture (Nelson 2020). Such development will rely on the presence of potential commercial markets and the biological suitability of any particular seaweed species for aquaculture, however, these are yet to be explored in any detail. The methods for growing other seaweed species of interest may vary depending on the species involved, as a variety of aquaculture methods are used throughout the world, including various types of longline culture, seabed planting, intertidal frames and strings, and floating cages (Barbier et al., 2019).

A number of previous studies have reviewed the potential for commercial aquaculture of seaweed species in New Zealand and have generally considered them as being unsuitable given the lack of seaweed aquaculture and processing experience and capacity, and the economics of producing mostly low-value species in a higher wage economy, such as New Zealand (Jeffs et al. 2001, Jeffs 2003, Hickman et al., 2003, Hayden 1988, Jeffs et al., 1999, Roberts et al., 2002, Te Puni Kōkiri 2009).

A recent regional review for iwi has recommended regenerative seaweed farming as a priority based on potential and generalised international market prospects, and the regenerative ecological aspects of seaweed production being well aligned with Māori cultural perspectives for productive activities utilising the environment (EnviroStrat 2020a). This review is vague on technical details but recommends sea lettuce (*Ulva* spp.) and common kelp as candidate species. Likewise, a recent proposal for establishing the GreenWave aquaculture production concept in New Zealand proposed a focus on common kelp, sea lettuce, wakame and giant kelp as candidate species (EnviroStrat 2020b). This conclusion was based on some market analyses which identified the most attractive markets for these seaweeds would be their use in the local manufacture of seaweed biostimulants, and animal feed/supplements. Existing market participants indicated the existing market domestic demand for seaweed was around 350 tonnes dry weight per year for use in agriculture/horticulture industries as soil conditioners and animal supplements.

Based on this recommendation a Greenwave-like seaweed aquaculture pilot project has been established in the Hauraki Gulf, which is initially targeting the production of *E*. *radiata* on existing mussel farms converted for the line culture of seaweed. The initial goal is to seed and grow up to 24 km of lines with this seaweed.

Market opportunities for higher value outlets for potential seaweed products generated from New Zealand, such as higher value bioactive and cosmeceutical extracts, were limited or difficult to identify from available infomation. The use of seaweed biomass for carbon offset trading was also identified as a market with potential for future development to support seaweed aquaculture production. Seaweed biomass may also have potential for use in the manufacture of novel biomaterials, such as biodegradable alternatives to synthetic plastics.

Potential Opportunities for New Zealand Seaweeds

To establish economically viable seaweed aquaculture in New Zealand it is highly likely that higher value end products will need to be produced. The identification of the seaweed species associated with these higher-value end products may help lead to the development of the successful culture of those species. A large number of studies have identified potentially valuable chemical compounds and bioactives from New Zealand seaweeds, including biosurfactants, phycocolloids, antioxidants, antimicrobials, natural colourants and tetrapyrroles.

Colourants

Natural colourants are sought after as food ingredients and for other products, such as cosmetics and textiles. For example, chlorophylls are green light-harvesting pigments found in all photosynthesizing organisms, including seaweeds of mainly *Chlorella* sp. Two chlorophylls, chlorophyll-a and chlorophyll-b, are currently used as natural colourants in food, pharmaceuticals, and cosmetics. Chlorophyll-a is a blue-green colour while chlorophyll-b is a green colour. The potential use of green seaweeds (i.e., *Caulerpa lentillifera*) and brown seaweeds (i.e *Stoechospermum marginatum*) as natural textiles dyes has been suggested as an alternative to toxic synthetic dyes (Ab Kadir et al., 2014).

Phycocyanin is a blue pigment derived from Cyanophyta seaweeds. It is one of the most common pigments commercially produced from algae, and several companies source phycocyanin from *Spirulina* species (Martelli et al., 2014). The algae is gaining popularity as a natural blue pigment with a high protein yield and easy extraction process, however, it is unstable to heating, preventing its use in some food products (Martelli et al., 2014). Another phycobilin, is R-phycoerythrin, a protein that is a major light-harvesting pigment in red algae

(Rhodophyta). It is commonly used as a fluorescent label in immunology and flow cytometry, and as a natural red dye in food and cosmetics. It has been extracted from several red algae including *Ceramium isogonum, Corallina officinalis, C. elongata, Gracilaria longa,* G. *fisheri,* and *Palmaria palmata.* For example, research on *C. elongata* shows that R-phycoerythrin comprises 0.06% of the alga by wet weight (Rossano et al., 2003).

Gelling and Hydrating Agents

The most commonly utilised seaweed products internationally are phycocolloids, water-soluble carbohydrates which have water-holding, emulsifying, and gelling properties, making them suitable for use in a variety of cosmetic products including shampoos, face masks, conditioners, and shower gels. Around 55,000 tonnes of phycocolloids are produced per annum worldwide from around 100 species, with an overall value of around US$600 million (Zemke-White & Ohno, 1999; McHugh, 2003).

The three most common forms of phycocolloids are agar, carrageenan, and alginate:

1. Agar is a galactose polymer obtained from the cell walls of some species of red algae. The majority of agar is produced from two species, *Gelidium* and *Gracilaria.* Species of *Gelidium* produce very high quality agar but are generally slow-growing making aquaculture uneconomic. *Gracilaria* sp. are faster growing but produce lower quality agar. In New Zealand several species of *Pterocladia* (closely related to *Gelidium)* are harvested for agar production (McHugh, 2003).

2. Carrageenan is the generic name for a family of water soluble, sulphate galactans that are isolated from red seaweeds. The majority of carrageenan is currently extracted from two species, *Kappaphycus alvarezii* and *Eucheuma denticulatum,* however, the highest quality and most valuable carrageenans are produced by *Gigartina skottsbergii, Sarcothalia crispata* and *Maizzaella laminaroides* (McHugh, 2003).

3. Alginates are linear copolymers based on two monomeric units, beta-mannuronic acid and alpha-L-guluronic acid. They are extracted from certain brown seaweeds, mainly from the genera *Ascophyllum, Durvillaea, Ecklonia, Laminaria, Lessonia,* and *Macrocystis.*

There are about 15 seaweed genera which occur in New Zealand that are known to produce good quality phycocolloids including species of the genera *Pterocladia, Gracilaria, Durvillaea, Gelidium, Gigartina, Porphyra,* and *Asparagopsis.* Considerable research has been conducted on extracting polysaccharides from New Zealand seaweeds, with the polysaccharide structure described for over 80 species of New Zealand seaweeds (Hurd et al., 2004). NIWA has previously researched the potential for aquaculture of several species of red seaweed which produce good quality phycocolloids. The functionality of phycocolloids can also be modified by enzymes, which isolate specific fractions for specific functionality (de Ruiter & Rudolph, 1997).

Preservatives

Antioxidants are molecules that bind with reactive oxygen species (e.g. -OH or –ROO radicals) preventing oxidation. They have two functions in cosmeceuticals; 1) they act as anti-ageing compounds, and 2) they prevent degradation of the products. Lipids are particularly susceptible to oxidation, producing undesirable volatile compounds and reducing the effectiveness of active ingredients. Oxidation in human tissue cells causes damage that contributes to ageing, cancer, and other diseases (Kiokias & Gordon, 2004). A wide range of compounds from marine organisms have been shown to have antioxidant activity, including pigments such as carotenoids and chlorophylls, the vitamins A, C, and E, phenolic substances produced by algae, and UV absorbing molecules such as mycosporine-like amino acids. Numerous seaweeds have been found to have antioxidative activity. Light harvesting pigments such as chlorophylls and phycobilins have also been shown to have antioxidant activity. Examples of antioxidant compounds identified in New Zealand seaweeds include; MAA in *Asparagopsis armata* (Karsten et al., 1998), *Bostrichia* sp., *Porphyra columbina*, *Strictosiohonia* (Hader & Sinha, 2002), sulfated polysaccharides in *Fucus vesiculosus* (Ruperez et al., 2002), bromophenols in *Polysiphonia urceolata* (Fujimoto & Kaneda, 1984), *Undaria pinnatifida*, (Stein & Borden 1984), dimethyl- sulfoniopropionate, *Porphyra haitanesis* (Zhang et al., 2003), agrailamide in *Martensia fraglis* (Takamatsu et al., 2003).

Antibacterials and Antifungals

Numerous antibacterial and antifungal compounds have been isolated from New Zealand seaweeds, including phlorotannins, sulphated polysaccharides, and terpenoids. In total, more than 20 species and genera have been identified (see Appendix 1). A few seaweed extracts are now included in cosmetic products specifically for use as anti-bacterial and anti-fungal agents. In 2001 Jean-Yves Moigne, director of the cosmetic company Algue et Mer, developed an anti-acne and anti-dandruff product extracted from a native New Zealand seaweed, *Asparagopsis armata.* Product descriptions claim that the extract kills the bacteria *Pseudomonas aeruginosa* and *Staphilococca* sp. (TermasWorld®, 2000 - 2005). The extract is sold under the trade name Ysaline15 (IMPAG, 2005), and can also be used as a natural preservative for cosmetics. Another commercial anti-fungal (anti-dandruff) product is Fucane HMW-FS, which contains the high molecular weight biopolymer fucoidan extracted from the brown seaweed *Ascophyllum nodusum* (IMPAG, 2005). Fucoidans are a group of sulphated polysaccharides found in certain brown seaweeds that have a number of bioactive properties.

UV Filters

Numerous shallow-water marine organisms have developed natural mechanisms for protecting their tissues against ultra-violet (UV) radiation, such as UV-absorbing molecules, the production of antioxidants that neutralize free radicals, and behavioural avoidance, to reduce exposure to UV radiation. The most common UV absorbing molecules in lower organisms are mycosporine-like amino acids (MAA), which are found in corals, marine invertebrates, bacteria, fungi, and algae (Dunlap et al., 1998). Researchers have now compiled databases that list the photoprotective compounds that have been identified in hundreds of species of microalgae, seaweed, and cyanobacteria (Jeffrey et al., 1999; Grtiniger et al., 2000; Hader & Sinha, 2003).

Mycosporine-like amino acids are a group of around 20 highly water soluble compounds with a basic cyclohexanone or cyclohexenimine structure (Daniel et al., 2004). They have been shown to be highly effective UV absorbing molecules with a maximum absorbance range of 310-360 nm. MAAs occur in a wide range of marine organisms and have been isolated from over 140 species of seaweed (Hader & Sinha, 2003), including many genera present in New Zealand, e.g., *Gracilaria, Porphyra, Palmaria, Corallina* and *Enteromorpha.* MAAs are typically found in the highest concentrations in algae, particularly Rhodophyta (red algae) (Shick & Dunlap, 2002) and bloom-forming dinoflagellates (e.g., *Gymnodinium catenatum, Alexandrium* sp., *Heterocapsa* sp., *Scrippsiella* sp., and *Woloszynskia* sp.) (Jeffery et al., 1999). The UV absorptivity of certain MAAs is comparable to synthetic sunscreens. For example, the UV-A absorption coefficient(s) of an algal MAA, shinorine, was found to be 44,670 M^{-1} cm^{-1} (Schick et al., 2000). In comparison, the absorption coefficient of two synthetic UV sunscreens, butylmethoxydibenzoylmethane and terephthalyidene dicamphor sulfonic acid, are 40,000 M^{-1} cm^{-1} and 45,000 M^{-1} cm^{-1} respectively.

Research is underway on the possibility of using natural MAAs and synthetic MAA derivatives as sunscreens. One disadvantage of natural MAAs is that they have limited stability once extracted (Dunlap et al., 1998), however, studies have found that their efficacy is retained if they are encapsulated in liposomes (Daniel et al., 2004). For example, the red macroalga, *Porphyra umbilicalis,* was found to contain 1.4% MAAs per DW alga, mainly comprising Porphyra-334 and shinorine (Groniger et al., 2000). In human trials, a cream containing 0.005% MAA encapsulated in liposomes inhibited lipid peroxidation by 37% after 2 weeks and increased skin firmness by 10% after 4 weeks. In comparison, a synthetic sunscreen containing 1% UV-A filters inhibited peroxidation by 35% and increased firmness by 7%, while a plain cream only inhibited peroxidation by 10% and increased firmness by 2% (Daniel et al., 2004). These results indicate that there is great potential to develop natural sunscreens from MAAs and a number of patents exist on certain natural MAAs (e.g. Nakamura et al., 1984; Bird et al., 1988).

There is an active research project evaluating New Zealand algal species for their UV radiation absorbing properties and sunburn immune response-modulating compounds (Fisher et al., 2021). As awareness towards the harm of sun damage grows, the market for sunburn prevention is projected to increase globally to NZ$4 billion by 2022 (Technavio, 2018). New Zealand and Australia have the highest rates of skin cancer in the world costing millions of dollars per annum in the treatment of sunburn, skin cancer and skin-ageing (McLeod et al., 2017). Synthetic sunscreens are not fully effective, have negative environmental impacts and potentially harmful side effects (Derikvand et al., 2017; Stiefel & Schwack, 2013). The artificial organic UV-absorbing compounds can be allergens, endocrine disruptors, influence thyroid levels and disrupt neurological development (Ichihasi et al., 2003; Orton & Wilkinson, 2004; Axelstad et al., 2011; Manova et al., 2015). The accumulation of sunscreens in the aquatic environment also causes deleterious effects on corals and other marine organisms (Downs et al., 2016). There is an opportunity to create high-value sunscreen products in New Zealand that lead to more favourable outcomes for both human health and the environment.

Anti-ageing bioactive compounds

Fucoidans are a group of bioactive sulphated polysaccharides widely dispersed in the cell walls of certain brown seaweeds. The primary structure of fucoidan is composed of a repeating chain of fucose sugars. Research on fucoidans has found that they have several beneficial properties, including antibacterial, anti-inflammatory, antifungal, antiviral, and anti-ageing activity (Rupez et al., 2002; Ponce et al., 2003; Smit, 2004; Zhao et al., 2018). Several cosmetic manufacturers include bioactive extracts from fucoidan-producing seaweeds in their cosmetics for their skin and hair conditioning and anti-ageing properties, as well as their anti-microbial and anti-viral properties (Ponce et al., 2003; IMPAG, 2005). The bladderwrack *(Fucus vesiculosus)* is probably the most common source of fucoidans for cosmetic products. Extracts of *F. vesiculosus* are included in several cosmetic products as skin conditioning and anti-ageing agents (e.g., Cellumend, 2003; Chesham Chemicals, 2005; IMPAG, 2005). Numerous other brown seaweeds also produce fucoidans, and extracts from the brown seaweed, *Ascophyllum nodusum,* are included in two anti-ageing products, Fucane LMW-LS and Poylphenole Asco PP, made by IMPAG (2005). Fucane LMW-LS contains low molecular weight compounds (0.2-1 %) that reportedly increase the roundness of fibroblasts, improve microcirculation, and increase collagen synthesis. Polyphenole Asco PP contains 0.2-5% phenols and fucoidans that act as antioxidants, preventing skin damage from UV and pollutants.

New Zealand seaweeds that have been found to contain fucoidans include *Scytosiphon lomentaria* and the introduced *Undaria pinnatifida.* New Zealand also has 30 species of *Fucus* (Adams, 1994), many of which are also likely to contain fucoidans. *Undaria pinnatifida* has a unique composition of monosaccharides and the fucoidan sulfated glactofuran. Comparatively, sulfated frucose is the fucoidan in most often isolated in other brown seaweed species (Koh et al., 2019). It has been demonstrated that the structural conformation, monosaccharide composition and increased sulfate content of fucoidan influences its bioactivity, and has been suggested that *U. pinnatifida* would contain a wide array of biological activities increasing its functional value in cosmetic and health products (Zhao et al., 2018). Fucoidan is mainly extracted from the sporophyll of *U. pinnatifida* using a variety of methods. Common methods yield different quantities of fucoidan with examples including acid extraction (3.9%) (Kim et al., 2007), ultrasonication extraction (33%) (Song et al., 2015) and microwave-assisted extraction (18.2%) (Rodriguez-Jasso et al., 2011). Efficient extraction requires significant cost and equipment and the consistency in quality of the product has been variable in New Zealand. As a high value seaweed product, this should be a key focus point in future development.

Anticancer

The sulfated polysaccharide fucoidan and carotenoid fucoxanthin contained in brown seaweeds have been demonstrated to have growth inhibition effects on various cancer cell types. Fucoxanthin has been shown to be particularly effective at inhibiting in-vitro neuroblastoma, and colon adenocarcinoma growth (Wang et al., 2014), while fucoidan exhibits similar effects on lung carcinoma and breast adenocarcinoma (Zhao et al., 2018). The quantity and antioxidant properties of fucoxanthin isolated from commercial New Zealand *U. pinnatifida* samples was found to be similar to other commercial samples from Japan and Korea, giving it large potential as a nutraceutical resource (Fung et al., 2013). The anticancer properties of fucoidan sourced from seaweed is influenced by its sulfate content and linking mode of the glycosidic bond in the polysaccharide skeleton (Zhao et al., 2018). It has been demonstrated that fucoidan isolated from *U. pinnatifida* is more effective at inducing apoptosis of cancer cells in some lines of melanoma and breast cancer than fucoidan extracts from *Saccharina japonica* due to the bond composition and increased sulfate content (Vishchuk et al., 2011). The specific fucoidan also displayed antimetastatic activity that can block cancer cell and basement membrane interaction (Zhao et al., 2018). The high sulfate content and specific glycosidic bond type gives fucoidan isolated from *U. pinnatifida* strong potential in anti-cancer nutraceutical applications. *Ulva* spp. have also been purported to have anti-cancer properties amongst other anti-viral, anti-coagulant, antioxidant applications associated with seaweeds containing high sulfated polysaccharides (White & White, 2020). The species is commonly beach cast during macroalgal bloom events and the development of a high value product would be beneficial. The sulfated polysaccharide, ulvan, derived from *Ulva* spp. could potentially be of similar or equal value to the fucoidans extracted from *U. pinnatifida* but further research is required (White & White, 2020).

Food and food additives

Red, brown and green seaweed has been integral in the diet of early Māori since the earliest records and according to mātauranga Māori, as both food (kai) and medicine (rongoā). Red macroalgae species of the Genera *Pryopia* (karengo), *Gigartina* (rehia) and *Ulva* (sea lettuce) are most commonly consumed, while the bull kelp (*D. antarctica*, rimurapa or rimuroa) was consumed and used for making containers (pōhā) for the preservation of the muttonbird (White & White, 2020). Some seaweed species were consumed whole while others were roasted or ground down for medicinal purposes to ease eczema and intestinal ailments. Karengo is used to treat sore throats, rimuroa is used for treating goitre, intestinal worms, and to reduce skin irritations and rehia is used for treating insect bites and as a cough medicine (Stark 1979, Riley 1994, Riley 2018).

Early European settlers utilised carrageenan in their milk puddings and dried *Pryopia* was sent to troops in the Second World War as a laxative (White & White, 2020). Recent research has shown seaweeds contain abundant nutrients, vitamins and minerals and low quantities of fat (Smith et al., 2010; Venkatraman et al., 2019). Only a small proportion of carbohydrates contained in seaweeds are digestible giving them a low calorific value. Seaweed is able to bind to some undesirable dietary components and reduce their accessibility and it has demonstrated that consumption of seaweed in conjunction with food reduces the metabolic response of high sugars, lowers cholesterol and increases satiety (Smith et al., 2010; White & White, 2020).

Undaria pinnatifida is a brown seaweed that is commonly consumed in larger quantities (>10 g per serving) while other New Zealand seaweed species (*M. pyrifera, E. radiata, Hormosira banksii*) are used as seasonings (<1 g per serving). The red seaweeds *Porphyra* / *Pryopia* sp. and green seaweed *Ulva stenophylla* are also used in smaller quantities as food items. Seaweeds can be an important source of minerals in the human diet. Potassium levels are variable across commercially sourced New Zealand seaweeds, with *U. pinnatifida* (123 g/kg) and *Macrocystis* (118 g/kg) containing the highest levels (Smith et al., 2010). Commercially produced *Macrocystis* also contains higher levels of iron (267.26 mg/kg) and calcium (37.6 g/kg) than *U. pinnatifida, Porphyra* and *Ecklonia*. Iron from these sources would require large quantities to be consumed in order to reach recommended daily intake (RDI), however, a considerable proportion of the RDI for potassium could be met with even 1 gram of seaweed and 10% of calcium RDI could be met with a 10 g serving of *U. pinnatifida* (Smith et al., 2010). *Porphyra* spp. has high concentrations of protein (26.36%) while comparatively lower levels were found in *U. pinnatifida* (14.21%), *Ecklonia* (9.78%) and *Macrosystis* (11.02%) (Smith et al., 2010).

Seaweeds can accumulate heavy metals, especially arsenic, from their environment and some countries have put regulatory limits on the concentration of heavy metals in seaweed products. In New Zealand, the only limit applies to inorganic arsenic levels that have a higher toxicity than organic arsenic. Analysis of the metal concentration in commercially available seaweed species in New Zealand found they were all within regulatory limits, with brown seaweeds generally containing higher levels than red and green species (Smith et al., 2010). Other contaminant metals were also investigated, with the highest concentration of mercury found in *E. radiata*, and lead in *U. stenophylla* but no levels exceeding the threshold to deliver harmful quantities of metals into the human diet (Smith et al., 2010).

The potential health benefits of fucoidan and fucoxanthin isolated from seaweeds appear to assist in managing chronic diseases, cancer prevention and performance enhancement in children (White & White, 2020). Functional foods as a product category had a global net worth of over US$ 130 billion in 2015 with particularly strong and growing demand in some Asian markets (White et al., 2014). In New Zealand, edible seaweed is sold fresh locally or dried and sold through commercial operators (Smith et al., 2010). Sea lettuce is the predominant species sold fresh, while a small number of species of red and brown seaweed are commercially dried. Food grade specifications of seaweed requires controlled drying conditions that are yet to be advanced to a large commercial production scale in New Zealand, with most food-grade production of seaweed products in this country occurring as a cottage industry. Current technologies for drying and milling are not cost-effective at a small scale, and this must be improved in order to increase scalability. Wakame has been identified as one of the species with the highest potential for use in functional foods due to its comparatively higher protein content, good levels of polyunsaturated fatty acids and fucoidan yield. Some fucoidan food products have already been developed in the form of cookies, drinks and noodles, with claimed benefits including reduced blood glucose, improved blood pressure, lipids and cholesterol (Kong et al., 2011; Zhao, 2011). Fucoidan from various seaweed species has also been demonstrated to have secondary antioxidant potential comparable to butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT), both synthetic antioxidants (Li et al., 2008). Fucoidan has been proven beneficial in the treatment of ailments including influenza, malaria and arthritis in animal trials (Hayashi et al., 2007; Chen et al., 2009; Park et al., 2010; Kumar et al., 2011). However, to label fucoidan as a supplementary therapeutic agent, pharmacokinetic interactions with other therapeutic agents must be investigated and deemed safe (Tocaciu et al., 2018). *Undaria pinnatifida* is used to manufacture food products by the Invercargill-based KiwiWakame Ltd and Auckland-based Pacific Harvest Ltd. There appears to be different distributions of varying strains (haplotypes) of *U. pinnatifida* most probably due to multiple introductions of the invasive species into the country, with some strains being of higher value for different products. Wild-harvested wakame may be better suited for the extraction of high value fucoidan and fucoxanthin but less suited for food products due to inconsistency of texture and blade form (White & White, 2020). Desirable food products could be achieved through selective breeding in an aquaculture environment if this species was allowed to be commercially cultured (White & White, 2020).

Skin finishing bioactive compounds

Little information is publicly available on the bioactive skin-finishing components of marine products that are commonly used in cosmetics. Some examples of marine extracts that are used as bioactive skin finishing products include an extract from the red seaweed, *Palmaria palmata* (sea parsley) which is used as an anti-irritant in shaving creams, hair care and skin care products (0.5-1 % wwt) (Engelhard Corporation 2005b). It is also used to boost microcirculation and reduce dark eye shadows (Chesham Chemicals, 2005). Extracts from a brown seaweed, *Laminara digitata,* are used for lipolytic activity and anti-cellulite and anti-ageing agents (Chesham Chemicals, 2005). While these seaweed species are not found in New Zealand, close relatives are, that warrant closer investigation for their bioactive content.

Anti-inflammatory bioactive compounds

In recent years there has been much interest in the search for natural marine anti-inflammatory compounds for pharmaceuticals (for reviews see Mayer & Hamann, 2004; Faulkner, 2000). Several New Zealand seaweeds (Genera or species) have been shown to produce anti-inflammatory compounds. Many of these compounds may also have applicability for use as topical anti-inflammatories in skin cosmetics. For example, a steroid compound (3-O-beta-D-glucopyranosyl clerosterol) extracted from the New Zealand green seaweed, *Ulva lactuca,* has been found to have potent topical anti-inflammatory activity. A dose of 1000 µg of the *Ulva* steroid produced a similar anti-inflammatory effect (62.3%) to 1000 µg of the reference drug (indomethacin), while a dose of 1500 µg of the *Ulva* steroid inhibited inflammation by 72.2% (Awad, 2000). *Ulva lactuca* is included in a few cosmetic products for its anti-inflammatory effect (e.g. Cblorofiltrat® Ulva HG by Chesham Chemicals, SeaPlus Renewal Cream by Alba Organics), though no specific patents for anti-inflammatory extracts from *Ulva* sp. could be found. Thus, there is good potential for the production of an anti-inflammatory compound from *Ulva lactuca* or one of the other 28 *Ulva* species present in New Zealand. 3-0-beta-D-glucopyranosyl clerosterol has also been isolated from *Codium deconicatum* and *C. iyengarii* (Ahmad et al., 1992; 1993). Other New Zealand seaweeds found to have strong topical anti-inflammatory activity include *Galaxuara oblongata, Cladophora* sp., and *Corallina* sp. Methanol extracts of these species inhibited oedema by 84%, 68%, and 61 % respectively, at a dose of 1000 µg. In comparison, the control drug indomethacin inhibited oedema by 88% (Bustos et al., 1992).

Thalassotherapy

Modern thalassotherapy or "seawater therapy'' was invented by the Frenchman Louison Bobet, in the 1960s. It involves using seawater and seaweed wraps to cleanse and rejuvenate the skin and is reported to confer other benefits including weight loss, reduction of cellulite, and relief from rheumatism and osteoporosis. The seaweed wraps are prepared by grinding or milling the seaweed and then rehydrating it to form a paste. The paste is applied to a person's body and may be warmed using infra-red radiation. Afterwards, the paste is removed or washed off, often using seaweed hydrotherapy. The most commonly used seaweed for thalassotherapy is *Laminaria* sp. (e.g. Natali Products, 2005; Phytomer, 2005), a Japanese kelp most commonly cultured in Japan. *Laminaria* sp. has high iodine and mineral content, which draws excess water out from the skin and also makes it suitable for the treatment of thyroid problems (Cellumend, 2003). *Undaria pinnatifida, Fucus vesiculosus* and *Delesseria sanguinea* are also used for various thalassotherapy treatments (Chesham Chemicals, 2005). Several New Zealand seaweeds including *Lessonia* sp., *Fucus* sp., *Delesseria* sp., *E. radiata, M. pyrifera,* and *U. pinnatifida* may have comparable properties which could be applied in thalassotherapy.

Deodorants/deodoriser compounds

Phlorotannins and chlorophylls have been identified to have natural deodorising activity and have the potential to be marketed as breath fresheners or personal deodorants. Research on three species of brown algae, *Eisenia bicyclis, Ecklonia cava* and *Ecklonia kurome* have found that phlorotannins produced by the seaweeds show deodorising activity stronger than other conventional natural deodorising agents such as chlorophyll or sodium copper chlorophyllin (Kita et al., 1990). One mg of ethyl acetate extract of *E. bicyclis* was able to completely deodorise a solution of 1 µg ml^{-1} of methyl mercaptan. Seaweed products are currently included in a small range of commercially available deodorant products (e.g., Dermoprotective Deodorant by Podovis), however, it is not clear if the seaweed extracts are used as the active deodorising agent. Phlorotannins have been found in several common New Zealand native seaweeds including *E. radiata, Carpophyllum* spp., and *Cystophora* sp.

Carbon offset potential

There is strong interest in the potential of farmed seaweed as a sink for anthropogenic carbon emissions (Sondak et al., 2017). Seaweed takes carbon from the atmosphere through photosynthesis at a significantly higher rate than terrestrial forests, giving it large potential as tradable carbon credits in a farmed application. Although not currently on the emissions trading scheme in New Zealand, there has been substantial interest in placing monetary incentives on this ‘blue carbon’. To remove carbon from the atmosphere, the seaweed must be sunk to great depths, stored long-term or turned into biofuel. When seaweeds are harvested and utilised in food products there is no net uptake of carbon as it is regenerated during respiration (Sondak et al., 2017). *Macrocystis pyrifera* captures carbon three times quicker than New Zealand’s most efficient terrestrial plantations of radiata pine and has a high net primary productivity of 5.25 kg CO_2 equivalents per m^2 per year (Rassweiler, 2018). This is significantly higher than other seaweed species found in New Zealand, *U. pinnatifida* (2.79 kg CO2 equiv./m2 /year) and *E. radiata* (1 kg CO2 equiv./m2 /year) (Chung et al., 2013; Kraan, 2017). The potential of farming *M. pyrifera* with a high degree of carbon sequestration is greater in the deep sea where low light, oxygen and temperatures may slow the rate of decomposition of both dissolved organic carbon (DOC) and particulate organic carbon (POC) to hundreds of years (Rassweiler, 2018). Companies are already investigating offshore opportunities in this space, however, there is a lack of understanding of the practical workings of sinking large quantities of seaweed in the deep sea. Seaweed biomass also has the potential to be converted to inorganic carbon by pyrolysis in the absence of oxygen, creating biochar, which can be used as an effective soil conditioner that has greatly slowed carbon release (Roberts et al. 2015). New Zealand seaweeds appear to show initial potential for this end use (de Bhowmick et al. 2018). There is also potential future potential in the conversion of seaweed biomass into bioenergy products including biogas and biofuels (Sondak et al., 2017).

Biomaterials

The unique biochemical composition of seaweeds provides opportunities for their use for the formulation of a wide range of novel biomaterials, including novel gelling applications, biodegradable substitutes for plastics, and building products (Daemi et al., 2016, Maiti 2018, Williams et al., 2021). For example, preliminary research in New Zealand suggests seaweed can be used as an effective replacement for synthetic products commonly used in manufacturing wallboard used in construction (Wannan, 2022). The wide range of opportunities for biomaterials from seaweeds appears to have received little other research attention in New Zealand, despite the potential opportunities for identifying novel seaweed biomaterials.

Animal feed and fertiliser

The production of animal feed and fertiliser is dominated by brown seaweed species in New Zealand. *Macrocystis* is commonly used to produce fertilizer and feed for pāua and sea urchin aquaculture by companies, such as NZ Kelp Ltd. (Gutierrez et al., 2006). *Durvillaea* sp are also harvested for fertilizer, with an increasing interest in seaweed from the domestic market as the popularity of chemical fertilizers diminishes in favour of more environmentally friendly alternatives (White & White, 2020). Traditionally popular exports to Australia, Brazil and the USA are expected to grow globally as demand increases elsewhere. Beach cast *E. radiata* is also prominent in the production of organic fertilizer and animal health supplements by New Zealand company AgriSea Ltd. This species of seaweed is not included in the quota management system for harvesting and research is yet to be published investigating the sustainability of harvesting non-beach-cast *E. radiata* (White & White, 2020).

The seaweed genus *Asparagopsis* has recently emerged as a possible solution for ruminant methane emissions through the dietary administration to ruminant animals (O'Mahony et al., 2021). Studies have demonstrated a methane reduction of between 40-90% by replacing <3% of the feed with *Asparagopsis* biomass (Kinley et al., 2020; Black et al., 2021). When the seaweed was included in a grain diet feed to cattle at 0.2% of feed, the methane production from the cattle was reduced by 98% (Kinley et al., 2020). Furthermore, the inclusion increased animal productivity, caused no negative impacts on the ruminant or product reported, and found no traces of the anti-methanogenic compound bromoform in the animal (Kinley et al., 2020; Black et al., 2021). In a country that relies so heavily on agriculture, research is currently being undertaken to explore the potential of farming *Asparagopsis armata* in New Zealand by companies CH4 and Seaforest. Concurrent research by scientific institutions, such as Cawthron, is occurring to increase the understanding of the life cycle and increase the yield of bromoform in the cultivated seaweed. Many questions remain around palatability and the methods of delivering the required seaweed supplements into grass-fed diets of ruminants in the New Zealand context.

Conclusions

New Zealand has a wide range of seaweed species (over 800) many of which may have potential for use in high value products or applications, such as cosmetic and nutraceutical ingredients. Some ingredients such as fucoidans and phycocolloids are already used in commercial cosmetic products, while research on other seaweed compounds, such as MAAs, have shown promising results and are currently subject to further research and development. The vast majority of compounds identified in this report are not restricted to particular species but are often found across numerous species, many of which are closely related to New Zealand species.

Extracts and compounds derived from seaweed are currently the most common natural marine products incorporated into cosmetics. The identification of topical anti-inflammatory compounds, phlorotannins, and fucoidans shows the greatest potential for novel cosmetic products from New Zealand seaweeds. Initial research on *U. lactuca* and *Galaxuara oblongata* extracts have shown potent anti-inflammatory activity, however, little commercialization of these compounds has occurred, suggesting a niche opportunity for a topical anti-inflammatory compound.

Phlorotannins and fucoidans from a small selection of seaweed species are already commonly incorporated in natural cosmetic products, however, there is a huge diversity of phlorotannins and fucoidans, with a corresponding diversity of functions. These compounds have also been shown to have several beneficial properties, such as antibacterial, anti-inflammatory, antifungal, anticancer, antiviral, anti-ageing, and deodorising activity. Therefore, there is a good probability that novel compounds can be identified and developed from New Zealand seaweeds that will confer the opportunity to develop aquaculture of high value seaweed species.

There is potential in the increased commercialisation of *U. pinnatifida* to target its unique and high value fucoidan. Although *U. pinnatifida* is an invasive species that is only currently harvested from mussel farms and from some coastal areas, it is likely that in the future the aquaculture of the species will be allowed (White & White, 2020). To achieve high value fucoidan products from this source, the quality must be closely monitored and this could potentially also be achieved through the utilisation of a land-based recirculating aquaculture system. Although *U. pinnatifida* has some potential, emphasis should be placed on native species, such as *Ulva* sp*.* for which the sulfated polysaccharide, ulvan, could potentially be of similar or equal value to the fucoidans extracted from *U. pinnatifida*. Further research into the fucoidan content and qualities of endemic seaweed species would be valuable through identifying the opportunities for developing nutraceutical products.

There is also an opportunity for New Zealand to be world-leading in the aquaculture of *Asparagopsis armata,* as a feed supplement for ruminants to reduce methane emissions. Similarly, increasing the availability and farming of *M. pyrifera* and *E. radiata* could be useful in supplying the growing global demand for animal health supplements and fertilizers. The aquaculture of these species has significant potential benefits for the environment, providing habitat for marine organisms, supporting the food chain and potentially contributing to carbon sequestration.

The small size of New Zealand and its existing seaweed industry means future commercial seaweed aquaculture production most likely lies in producing high value and value-added products for export markets. The increasing demand for 'environmentally friendly' and 'green' products and the infancy of the New Zealand seaweed industry provide significant opportunities for future commercial development, provided those product opportunities can be clearly identified and exploited.

The coastal aquaculture industry in New Zealand has a history of successful growth, based largely on effective innovation for at sea operations, land-based handling and processing, including creating efficiency at greater scales of production. This experience and capacity will be invaluable for initiating and growing a seaweed aquaculture industry that can supply the raw material for preparing market products. However, the identification and commercialisation of novel marine bioproducts that are of sufficiently higher value to make seaweed aquaculture viable, is an area in which the New Zealand aquaculture industry is relatively inexperienced. Research and development for identifying and developing novel seaweed products, and preparing those through innovative processing technology and taking them to market will be key steps to generating prosperity from seaweed aquaculture in New Zealand.

The New Zealand government has recently recognised the opportunity that seaweed aquaculture provides and has committed to supporting the development of a seaweed aquaculture sector in an effort to reach its goal of realising $3 billion in revenue from the aquaculture sector by as soon as 2030 (Ministry for Primary Industries, 2021). The government is supporting the development of a seaweed aquaculture sector framework that aims to better facilitate the development of an emerging and profitable seaweed aquaculture industry for New Zealand, whilst also maximising environmental outcomes (Bradly et al, 2021.

A significant portion of the existing aquaculture industry in New Zealand is owned by Māori, and this is set to continue to increase, with ongoing allocation of new farm space and corresponding Māori investment in development. There is initial high level of Māori interest in seaweed aquaculture with a number of Māori aquaculture enterprises engaged in research and pilot development of seaweed aquaculture operations. This includes the development of *E*. *radiata* farm space in the Hauraki Gulf, with the aim of supplying product to existing Māori-owned seaweed processing and product distribution and sales capacity. The New Zealand government has also committed to supporting the growth and development of Māori aquaculture through its aquaculture development strategy (Ministry for Primary Industries, 2021). Coastal aquaculture of seaweed is a relatively environmentally benign activity, which may also generate a range of environmental benefits, including carbon sequestration and artificial habitat creation (Clark et al., 2021). From this perspective, seaweed aquaculture fits well with widely-held Māori perspectives on environmental sustainability of productive practices.

The wider commercial exploitation of endemic seaweed species, especially where it may be based on or incorporate mātauranga Māori (e.g., rongoā of targetted seaweed species), raises issues around rights to indigenous biodiversity (Wheeler et al., 2021). It has been recommended that positive progress in this space will rely of the development of appropriate frameworks to partner with Māori to progress seaweed aquaculture for ensuring mutual benefit.

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