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Asparagopsis R&D Review

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For: Australian Sustainable Seaweed Alliance

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***Asparagopsis* R&D Review**
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Contents

Executive summary

Asparagopsis has been gaining attention for its climate change mitigation potential since its methane reducing capabilities as a cattle feed were discovered in 2006. In the last three years, since the Australian Seaweed Industry Blueprint identified *Asparagopsis* as having significant potential as an emerging industry, many companies have entered the market and are working hard to achieve commercial production. However, *Asparagopsis* is still very much a nascent industry, with a lack of accessible knowledge and expertise resulting in significant delays to market. A National Hatchery Network has been identified as having the potential to fast-track production and support current and emerging growers. Current state of knowledge was assessed against the major supply chain elements; wild population assessment, hatchery, cultivation, processing/manufacture of products and product and market development. Surveys and interviews with seaweed farming companies, state governments, and research groups actively working on *Asparagopsis*, identified a suite of knowledge gaps and challenges to the industry and opportunities for a National Hatchery Network (NHN). A lack of information sharing and collaboration appeared as the biggest anticipated challenge, with many growers reporting a lack of access to basic cultivation information and expertise, issues with contamination of cultures, hatchery design and technology needs and seeding methodology suitable for marine cultivation. A small minority of stakeholders reported that there is no lack of knowledge but research findings are not publicly available. There are also several patents pending from at least three companies in Australia and internationally but without further details of those patents it is hard to assess if formal IP exists. However a report published in 2023 concluded that "the successful implementation of a nursery stage that supports cultivation of *Asparagopsis* in sheltered nearshore environments is yet to be demonstrated" (Visch et al 2023). Therefore, it is the opinion of the authors that there is a major knowledge and skills gap relating to hatchery production methods, and this conclusion is also supported by the very small production volumes and product sales in market. The NHN will therefore need to undertake considerable foundational cultivation research and create an environment to share information if we are to make available knowledge and expertise to accelerate industry growth in Australia. A full list of priorities are presented in Table 1. Additionally, while significant Federal Government investment is going into product trials through the Livestock Emissions Reduction Program, the review highlighted that until there is a livestock Emissions Reduction Methodology in Australia then there will be a significant barrier to adoption of this technology for customers.

Table 1 List of NHN priorities identified through the review and surveys undertaken in this report

Asparagopsis **R&D priorities according to supply chain element**
- Share existing and new knowledge, IP and know-how through training, workshops, handbooks/guides and meetings
Wild Population Assessment
- Develop protocols for identifying wild populations, collecting broodstock and monitoring seasonality and maintain a database of all records
- Disseminate research findings and genetic data for development of government translocation regulations
Hatchery
- Focussed research to close the life cycle, produce spores and seedlings on demand
- Develop techniques for seeding substrates, growing seedlings for deployment, and transport of seedlings to cultivation sites
- Optimise seeding techniques to achieve consistent, replicable and reliable seed stock for farmers
- Develop contamination management techniques
- Maintain clean broodstock repository for all growers participating in the NHN
- Develop hatchery technology and infrastructure through experimentation
- Make expertise available by drafting and sharing hatchery design guide, operation manual and standard operating procedures
- Research collaborations to develop biosecurity protocols for internal handling of cultures and transport/translocation of broodstock and seeded material
- Research quality assurance practices for all stages of the hatchery process to maintain and improve health of seed stock provided to farmers
Cultivation
- Operational support and field advice for the successful grow-out of provided seed, *in situ* monitoring of deployments, and transparent reporting of production results by growers
- Share emerging scale-up knowledge, research findings and technology available for cultivation stage
- Assist growers to access technology collectively where possible e.g. engineering design
- Workforce development for the seaweed industry
- Supply chain production cost analysis and benchmarking
Processing and Product Development
- Contribute to a Carbon Emissions Reduction methodology

1 Introduction

For decades there has been considerable seaweed farming occurring outside Australia, with significant volumes of Euchematoids/Carrageenophytes being produced in Southeast Asia, large-scale nori and kelp farms in North Asian countries, and innovative technologies being developed in Europe for commercial scalability. Even so, seaweed production, particularly Euchematoids, is not reaching its full potential, nor filling the demand for food products, setting agents, fertilisers, pharmaceuticals, biodegradable plastics, climate reduction schemes and restorative programs. Most production occurs in Asia but this is limited almost entirely to highly manual, subsistent techniques which would not be economically viable in Australia. Since vegetative out planting is most common, the industry is not currently dependant on hatcheries and their development has not been a focus. Kelp production in Europe is also gaining attention for its fast development of this emerging industry; however, scale is still limited (Buschmann et al. 2017, Filieres 2020). The European growers are developing exciting new industrial technologies, primarily for kelp farming, but farms are still only relatively small and production is only several hundred tonnes per year (Araújo et al. 2021, Hermans 2023). Even though the seaweed industry has been underway for decades, production is still limited, and it is therefore understandable that with only three years of development, the Australian seaweed farming industry has a long way to go.

The Australian Seaweed Industry Blueprint was published in 2020, highlighting the opportunity for the Australian seaweed industry to achieve $100 million gross value of production (GVP) within 5 years if critical industry development activities received funding (Kelly 2020). *Asparagopsis* was identified as the species with the biggest potential and, since this time, many new companies focussing on *Asparagopsis* cultivation have been established. A review of industry needs, and ways to support seaweed farming in Australia (Kelly 2022) highlighted the benefits of establishing a National Hatchery Network (NHN) and a dedicated research capability and knowledge repository for the benefit of all companies and growers. The NHN will focus on *Asparagopsis* and lay the foundational groundwork for a hatchery network for other species to be integrated or fast tracked by replicating this process.

There are two species of *Asparagopsis* found in Australia, both of which are endemic (Figure 1). *Asparagopsis armata* is a cool temperate species found around southern Australia from the Abrolhos Islands in Western Australia, south around Tasmania and north into New South Wales. The second, *Asparagopsis taxiformis,* is a warmer water species with a sub-tropical /tropical distribution and is found all around northern Australia, extending to Perth in Western Australia, but is also found in South Australia.

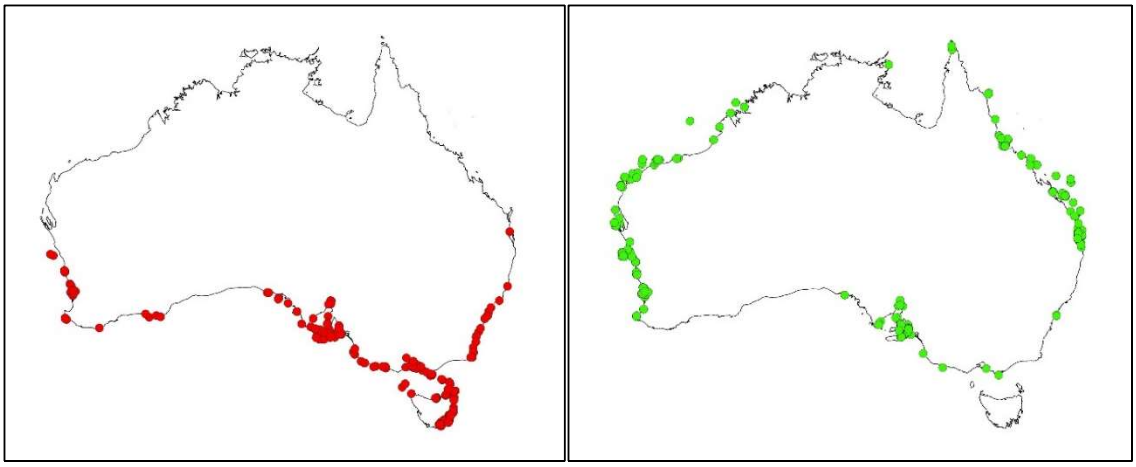

Figure 1 Documented records of *Asparagopsis armata* (red, left) and *A. taxiformis* (green, right). Source: Atlas of Living Australia

When these macroalgae are observed in the wild it is relatively easy to distinguish the two species. *Asparagopsis taxiformis* grows to approximately 20 cm with fluffy fronds and a complex 'rhizome' mat attached to reef. *Asparagopsis armata* is generally found growing epiphytically on other algae, using distinctive harpoon or hook-like appendages to tangle with large seaweeds (Figure *2*). *Asparagopsis* is a red algae (Rhodophyta) with a complex life history making it challenging to cultivate. There are two main phases in the life cycle; the easily observable gametophyte stage, which is haploid, and the small fluffy 'pom poms' around 1cm in size, referred to as the tetrasporophyte, which are diploid. *Asparagopsis* alternates between these two stages by producing spores throughout the year. This information is important as the life phase cultured will depend on the type of farming planned. Both species are known to have strong seasonal periods of growth and reproduction, and it is, therefore, important to understand regional ecological patterns in order to farm local strains.

Figure 2 Examples of *Asparagopsis armata* (left) and *A. taxiformis* (right) taken in Western Australia

Even though the Australian Seaweed Industry Blueprint was published over three years ago, significant government funding continued to be invested in *Asparagopsis* R&D in an ad-hoc manner across different states, universities, industry participants and supply chain elements. Despite the many research initiatives unearthed in this report and the establishment of at least six *Asparagopsis* farming companies in Australia, there is still no consistent commercial production of *Asparagopsis*. The reason for the lack of product is not completely clear due to commercial confidentiality; however, there is a distinct lack of access to knowledge and technical expertise for the industry. Limited scientific species-specific knowledge and lack of commercial seaweed farming experience in the country, has resulted in unanticipated delays. The NHN would benefit the industry by alleviating some of these road-blocks and provide scientific capability to support emerging and existing farmers.

The most recent published review of *Asparagopsis* farming knowledge was Visch et al. (2023), who investigated the feasibility of offshore seaweed farming, and included *Asparagopsis* as a case study. They supported the assumption that general knowledge regarding hatchery techniques is locked up in commercial operations and is largely publicly unavailable. Due to a lack of published literature, they concluded that 'the life cycle has not yet been closed (from gametophyte to gametophyte), and so biomass production remains reliant on harvest of wild stock and/or fragmentation of the various life stages' (Visch et al. 2023). Visch et al. (2023) also stated that 'At the time of writing, the successful implementation of a nursery stage that supports cultivation of *Asparagopsis* in sheltered nearshore environments is yet to be demonstrated'. A report published in 2022 by AgriFutures Australia also reported, that at the time of writing, there were no large-scale commercial *Asparagopsis* farms in operation in Australia, and that most of the intellectual property was held by private interests (Ball et al. 2022).

Before initiation of the NHN can begin, it is critical to explore and understand the major knowledge gaps and bottlenecks to *Asparagopsis* production and to collate the existing literature, so that effort and investment is not duplicated and wasted moving forward. It is also important to understand the needs and status of other seaweed growers, and the potentiality for them to share their research for the betterment of the industry. An understanding of knowledge gaps will allow the NHN to better fill the needs of the industry, and conduct seaweed research that is needed to accelerate commercial production (e.g. production of seeded lines).

1.1 Seaweed supply chain

When understanding the need for the NHN, the best way to record the knowledge gaps is to group them under major sections of the supply chain. Figure 3 shows a schematic describing the supply chain for *Asparagopsis* production and the major research undertaken or required for each step. The supply chain starts with observing and understanding local wild populations and understanding the natural spatial and temporal patterns in distribution for each of the life-stages (Wild Population Assessment), then moves to the Hatchery where broodstock is stored and managed and where reproduction is induced for farming. The next step is Cultivation, where research focuses on optimising growth, scale-up, monitoring and production. The cultivation of *Asparagopsis* can be divided into land-based tank cultivation or mariculture (at-sea grow-out), and research demands differ depending on which technique is used. After the growing steps in the supply chain, focus turns to Processing and Product Development.

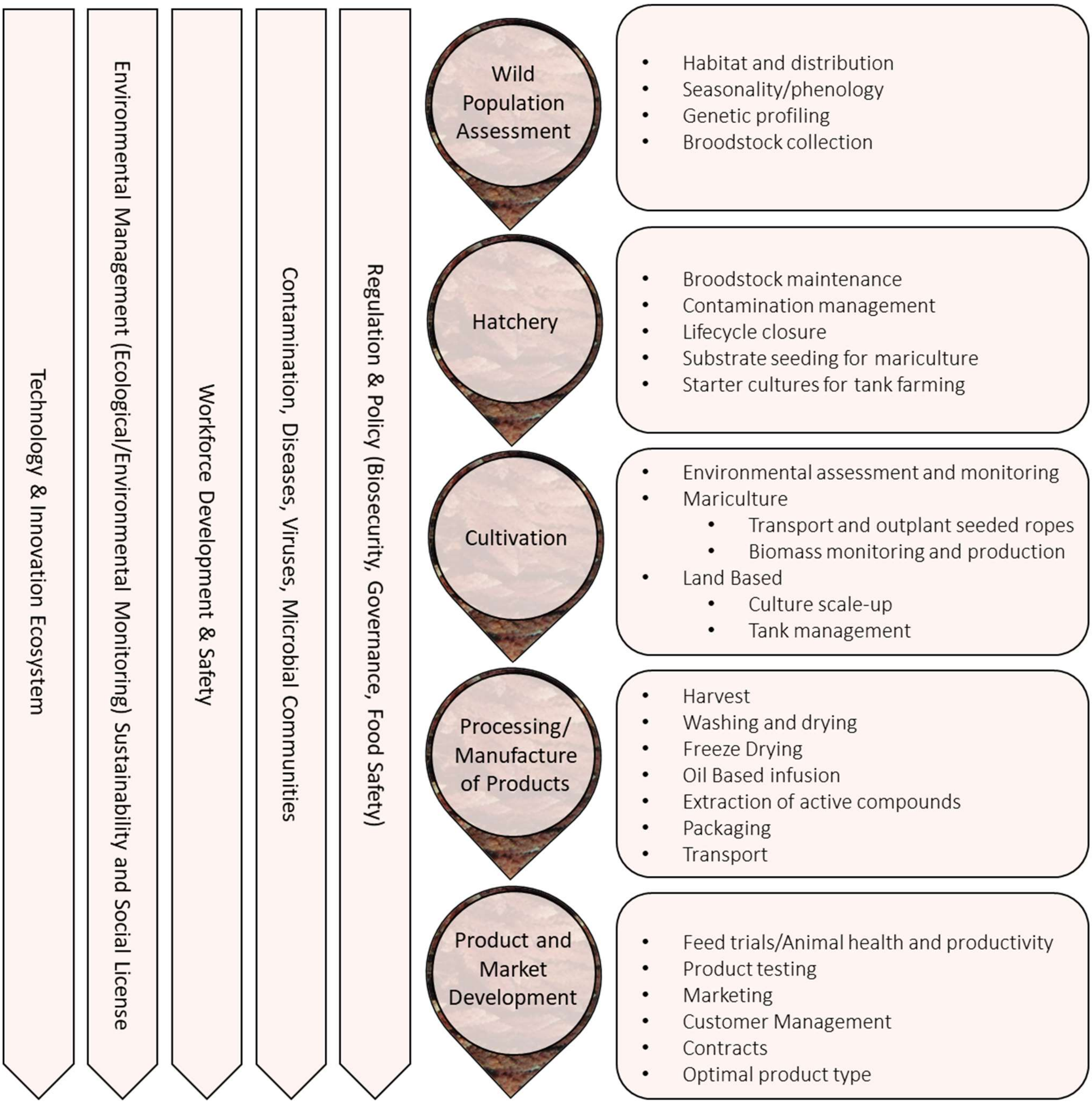

Figure 3 Supply chain diagram showing the major steps to commercial production of *Asparagopsis*

2 Methodology

2.1 Literature searches

In order to assess the current state of knowledge, and to better understand where knowledge gaps exist, an extensive literature search was conducted. This commenced with a thorough search using Google, as well as various university library databases and existing online bibliographies. The keywords used in these searches included '*Asparagopsis*', '*armata*', '*taxiformis*', 'research', 'cultivation', 'hatchery', 'methane', 'seaweed', 'farming', 'aquaculture' and various combinations. All literature identified was entered into a Zotero reference management database. Every attempt was made to obtain PDF copies of these papers and these were stored in the reference library. Once a basic bibliography was established, deeper literature searches were carried out by examining and extracting any additional relevant publications from the reference lists of the papers collected.

This preliminary search uncovered much of the grey (i.e. open access reports, theses, conference reports, other unpublished work) and published literature. From here, project portals for major funding bodies (e.g. AgriFutures Australia, FRDC, MBCRC, ARC, FutureFeed, IP Australia, ACIAR) were searched for existing and ongoing funded research projects. All of the papers and projects from these searches were tabulated in an Excel spreadsheet for further analysis (Appendix A).

2.2 Stakeholder survey and interviews

The literature search was only able to uncover research which was publicly available, or currently underway through a public funding body. With considerable R&D being undertaken through private enterprise, much of the knowledge currently being generated is not publicly available. In an attempt to capture some of this unpublished information and develop a more thorough understanding of the state of knowledge for *Asparagopsis* cultivation, a 17-question survey (see Appendix B) was sent to all current ASSA members who have expressed an interest in, or are actively pursuing, *Asparagopsis* farming, as well as any other known growers in Australia. This survey was also sent to any other non-farming groups associated with *Asparagopsis* production (e.g. FutureFeed). See Table 2 for full list of stakeholders contacted for this survey, and Figure 4 shows the locations of these stakeholders. A separate survey was sent to representatives at government agencies within each state, which had many of the same questions as the stakeholder survey but with several directed more toward government collaboration, funding and licensing/permitting (see Appendix C). Following completion of the survey, the stakeholder was asked to participate in a 45-minute interview to discuss their survey responses and gather a clear understanding of their current research status and their views on the role of a NHN in Australia. Some companies not working towards commercial production, e.g. research bodies, were not asked to complete the survey, but an interview time was requested. In most cases, stakeholders were contacted with a follow-up email to encourage participation. A deadline was imposed to encourage stakeholders to return surveys by the end of May 2023, and a third email was sent to those who had not responded a week before the deadline.

Table 2 List of all stakeholders contacted for input into this report, either through survey or interview. Their contribution and responses have been de-identified

Company / Department	Contact	Participant Type
ACIAR – Fisheries Research	Ann Fleming	Government
Australian Seaweed Institute	Jo Kelly	Company/ASSA
CH4 Global	Adam Main	Company/ASSA
CleanEyre Global	Almendra Rodriguez-Dominguez	Company
CQUniversity	Emma Jackson	Research
Fremantle Seaweed	Chris de Cuyper	Company/ASSA
FutureFeed	Eve Faulkner	Company/ASSA
Greener Grazing	Josh Goldman and Leonardo Mata	Company
Harvest Road	Michael Brooker	Company/ASSA
Immersion Group / University of Western Australia	John Statton	Company / Research
James Cook University	Dean Jerry	Research
Sea Forest	Sam Elsom	Company/ASSA
SeaStock	Tom Puddy	Company
South Australian Research and Development Institute (SARDI)	Sasi Nayar	Government Research
Tassal	Justin O'Connor	Company/ASSA
University of Sunshine Coast (USC)	Nick Paul	Research
University of Tasmania (UTAS)	Catriona Macleod	Research/ASSA
University of Technology Sydney (UTS)	Manoj Kumar	Research
Department of Natural Resources and Environment Tasmania	Dianne Maynard	Government
Department of Primary Industries and Regions, South Australia	Shane Roberts	Government
Queensland Department of Agriculture and Fisheries	John Dexter	Government
Victorian Fisheries Authority	Jo Klemke	Government
Department of Primary Industries and Regional Development, Western Australia	Steve Nel	Government
Department of Primary Industries, New South Wales	Ian Lyall	Government
Northern Territory Government	Matthew Osborne	Government

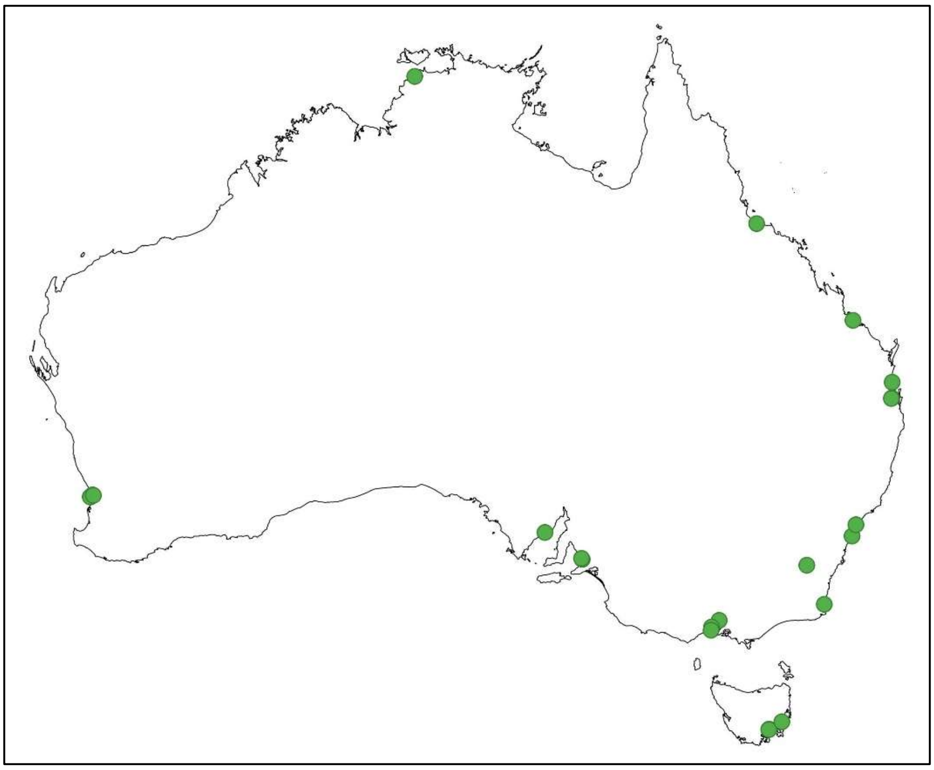

Figure 4 Location of all stakeholders who were contacted to complete the *Asparagopsis* R&D Review survey. One stakeholder was situated outside of Australia, and was included as they are leading experts in *Asparagopsis* cultivation research, and have expressed an interest in working in Australia.

3 Current state of knowledge

3.1 Literature searches

The extensive literature and project searches uncovered 142 *Asparagopsis*, from around the world, related research documents and projects (Table 2; Appendix A); including 72 published articles, 34 patents and 26 ongoing and completed research projects. Each article or project was allocated to a category in the supply chain according to its main topic of focus; however, in some cases articles spanned multiple categories and in these cases were counted twice (e.g. a paper with work relevant to both Hatchery and Cultivation was included in both categories but was only added to the total number of articles once). The most records were attributed to the Product Development research, which is largely made up of works investigating the methane reduction properties of *Asparagopsis* in cattle feed, of which there are a considerable number. The category with the least amount of information is the Processing and Manufacture of Products, of which only seven articles were discovered. Only fifteen papers or projects were discovered which contained information relevant to hatchery research.

Table 3 Summary table of research articles and projects discovered for this report, also broken down by supply chain element. The full table of records is presented in Appendix A.

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Type of Article	Number of records
Research project	26
Published literature	72
Patent	34
Presentation	10
Supply Chain Element	**Number of records**
Wild Population Assessment	37
Hatchery	15
Cultivation	32
Processing/Manufacture of Products	7
Product Development	57
Total number of articles	**142**

3.2 Wild population assessment

Wild population assessment encompasses any *in situ* research that has been, or needs to be, undertaken to understand the natural spatial and temporal patterns in distribution, growth, reproduction, population dynamics, natural bromoform concentrations or genetics. This fundamental ecological research is critical to establish the best conditions required to most effectively farm *Asparagopsis* at a local scale. This work is largely focussed on 1) mapping the seasonality of the various life-stages, as this can directly impact farming both on land and mariculture, and 2) defining spatial patterns in *Asparagopsis* occurrence, as this can help to guide the selection of optimal farming areas. This supply-chain step also includes the collection of broodstock for hatchery use and the wild-harvest of gametophyte which has subsequently been deployed on mariculture leases (Zanolla et al. 2022a).

There have been no direct methodological papers that describe population assessment, nor any describing methods for broodstock collection, only a few which mention the wild collection of reproductive material (Mickelson 2013). There are several papers which report occurrence, and in many cases, this includes the lifecycle phase of the plants, the habitat type, the time of year, and list details of the location (e.g. coordinates). This can be helpful in understanding habitat requirements and add small pieces to a bigger picture regarding seasonality. It is important to note that there is considerable regional variability in *Asparagopsis* seasonality, growth and habitat preference (Mata et al. 2016), meaning that if literature does not exist for a specific location, it is unlikely that data from further afield will be relevant.

There have been several papers which describe local conditions and make suggestions for farming based on ecological studies. There is a number of publications which attempt to map patterns of invasion and determine where populations originated from and the extent of their invasion (Andreakis et al. 2016, Preuss et al. 2022, Zhao et al. 2022). In many cases these include genetic coding information and could be incorporated into a genetic database within the NHN. Zanolla et al. (2022a) gives a detailed summary of all genetic mapping which has been undertaken for *Asparagopsis* since 2007, which could form the basis of a national database for *Asparagopsis* genetic structure.

There are also several papers which actively document seasonality and phenology from various locations around the world (Tsuda 1982, Chualáin et al. 2004, Zanolla et al. 2017); however, these data vary considerably between papers, and anecdotal observations from the field. These discrepancies, when combined with the high level of variability between regions and even within populations, highlight the need for location-specific *in situ* research and monitoring. Thus, any new seaweed farming regions being established would benefit from a year-round assessment of their local populations to understand their specific farming requirements.

Current research on *Asparagopsis taxiformis* genetics is being undertaken by the ARC Research Hub for Supercharging Tropical Aquaculture through Genetic Solutions. Seaweed is among one of five taxa being investigated for genetic lines for fast growth led by James Cook University and the University of Queensland with Sea Forest as the seaweed industry partner. The program will run for five years and the ARC is investing $5 million to cover pearl oysters, barramundi, prawns, seaweed, and grouper. No deployable outcomes or collaborations are expected to be made available to broader industry due to commercial in confidence.

Stakeholders highlighted a Marine Bioproducts Cooperative Research Centre (MBCRC) project being undertaken in Tasmania in conjunction with the Department of Natural Resources and Environment (TASNRE) and Sea Forest to collect baseline data including mapping the distribution, abundance and chemical variation in *Asparagopsis armata* around Tasmania. TASNRE are also undertaking a 'Baseline Seaweed Health Project' to understand native microbiome of *Asparagopsis* to inform future disease analysis. The interview with the South Australian Research and Development Institute (SARDI) also determined that results from an FRDC funded research project 'Cultivation trials of the red seaweed *Asparagopsis armata* and *A. taxiformis*' will give a better understanding of natural seasonal patterns within *Asparagopsis* populations around South Australia.

3.3 Hatchery

This step is most significant for the establishment of the NHN as this highlights where research efforts need to be focussed. Hatchery-related literature will be most important in informing how the NHN might integrate with current farming processes, and if the outputs of a NHN will be in demand. The Hatchery part of the supply chain includes all steps after the collection of wild plants/broodstock up to deployment at sea, or scale-up on land. This includes, contamination management, starter culture maintenance, life-cycle closure and line/substrate seeding and care. While the seeding of substrates is specific to ocean-farming, all other aspects are relevant to both techniques, as considerable stocks of tetrasporophyte will need to be established and managed for both processes.

Hatchery design and technology

When it comes to setting up a hatchery or land-based *Asparagopsis* farm, there is no readily available guidance for new starters. Start-ups with a foundation in aquaculture, such as those growing shellfish and fin-fish who are looking to diversify, often re-purpose existing hatchery designs and technology. New starters often rely on infrastructure designed for microalgae farming, like raceway tanks and photo-bioreactors, as well as techniques for inoculation and scale-up. There are a few guides for seaweed farming, such as the New England Seaweed Culture Handbook, which focusses on kelp, *Gracilaria*, *Chondrus crispus* and Nori, and provides detailed methodologies including equipment and some tank designs (Redmond et al. 2014). A patent (WO2021/150450 Bioreactor and method for culturing seaweed) details the use of a bespoke bioreactor to harvest spores released from *Asparagopsis* tetrasporophytes, and may provide some guidance in the design of a new hatchery. There is no dedicated publicly available research for *Asparagopsis* hatchery set-up or appropriate infrastructure, and in most cases new starters try to replicate what is published by the bigger growers in news articles and social media. In these cases, it cannot be known whether the designs worked well for *Asparagopsis*, and unfortunately this can lead to the same mistakes being made many times over.

Contamination management

Commercial companies are reporting contamination to be a major problem with cultivation. When broodstock is collected from the ocean, associated species are also collected, including bacterial, micro- and macro-algal and invertebrates (Zanolla et al. 2022a). In many cases, when presented with optimal conditions these competitors grow faster than *Asparagopsis*; competing for space, light and nutrients, whilst also resulting in proportionally less bromoform in the final harvest. This problem increases exponentially with scale and growers are constantly searching for solutions. Only one paper exists which references contamination for cultivated *Asparagopsis* (Dishon et al. 2022), but while these authors presented a technique to quantify contamination, they offered no solutions to the problem. There is literature that addresses contamination management for other seaweed species, but it is not yet clear which techniques will be useful for

Asparagopsis (e.g. Redmond et al. 2014). The FRDC funded research project 'Cultivation trials of the red seaweed *Asparagopsis armata* and *A. taxiformis*' led by SARDI has also been hampered by contamination, leading to a loss of hatchery and cultivation data which would benefit the industry. Unfortunately, this project has not resulted in any published research outputs due to commercial in confidence at the time of writing.

Life cycle and seeding lines

There are several papers which induce tetraspore production (Oza 1977, Guiry and Dawes 1992) giving growers some leads to follow for hatchery development. These papers report tetrasporogenesis, but not spore viability, germination, gametophyte success or growth. There is no information regarding the survival and culture of the subsequent gametophytes, and no reports of successful line seeding or deployments of these at sea. There are also two papers which highlight the variability in conditions for spore production, suggesting significant variability with population location and that techniques will need to be adapted for each region and strain (Guiry and Dawes 1992, Chualáin et al. 2004). One survey respondent, with years of experience cultivating *Asparagopsis,* highlighted the challenges of achieving consistent spore production and recruit survival, and emphasised that years of research is required and there is no 'silver bullet' for cultivation. There is no publicly available literature which reports line seeding and deployment attempts or success.

The MBCRC, the FRDC and the University of Technology Sydney partnered for a project titled, 'Overcoming propagule supply bottlenecks for seaweed production', which planned to undertake research into the use of the novel practice of protoplast isolation for *Asparagopsis* cultivation. This technique has been successful for some species of seaweed, creating a living plant cell without a cell wall (protoplast) and is believed to offer opportunities for propagation and plant regeneration including breeding, hybridization, genetic engineering and transformation. Whether the use of protoplast development was successful for *Asparagopsis* cultivation will be made available soon.

Tetrasporophyte maintenance

The hatchery will be expected to maintain stocks of tetrasporophyte, either for seeding ocean farms, or as starter cultures for tank cultivation. Management of contamination will be of the utmost importance in this case, and managing the health of stocks will be a priority over comparable growth and bromoform production rates. There is a range of articles detailing optimal culture conditions for growth, but few which focus on maintaining cultures. See Section 3.4 for IP relating to tank cultivation.

3.4 Cultivation

After the hatchery process, the scale up and farming phases will begin and this step in the supply chain is referred to as Cultivation. This is dependent on which technique the farm is employing; land-based tank cultivation or mariculture (Chualáin et al. 2004). In the case of land-based cultivation, the major areas for research focus will be on scale up and production optimisation. For mariculture, research focusses on transport, handling, deployment and monitoring and any other novel techniques to boost biomass and bromoform production.

There is a relatively extensive literature base around land-based farming processes and optimal conditions for tank cultivation mainly focussed on the tetrasporophyte phase of *A. armata*; however, there are significant discrepancies in reported production numbers and ideal growth conditions (Mata et al. 2006, Schuenhoff et al. 2006, Zanolla et al. 2022b), and this is likely to be a result of regional differences in growing conditions. Schuenhoff et al. (2006) reported growth rates of over 100 g DW/m^2/day growth for *A. armata* tetrasporophyte under specific conditions using waste water from fish farms in Australia. Zanolla et al. (2022b) reported 18% growth per day for *A. armata* tetrasporophyte using laboratory grade nutrients and small experimental cultures in Ireland. Despite the fact that this literature exists, there is still no commercial production using these techniques, and a general consensus among stakeholders that usable knowledge for tank farming is limited. The techniques used in these papers were applied in small-scale experiments, under controlled conditions, and seem relatively simple to replicate, so if these numbers were representative of actual tank growth rates, then companies should certainly have achieved commercial production in the past three years.

Considering that bromoform is the sought-after active compound which is stored in *Asparagopsis* cells, and the main reason for its methane reducing potential, there is almost no publicly available information on concentrations and optimisation. Improvement in bromoform concentration is even more critical than growth rates and biomass production. There is one paper which looked at the trade-off between increased growth and bromoform production for the tetrasporophyte of *A. armata* in tank cultivation (Paul et al. 2014) and another that found that the addition of hydrogen peroxide to *A. taxiformis* tetrasporophyte prior to harvest may boost concentrations (Mata et al. 2011). There is another paper which investigated the potential for natural variation in bromoform in wild populations of *A. taxiformis*, which could be relevant to ocean farming (Mata et al. 2016). However, no work has been completed into techniques which could optimise the production/concentration of bromoform within the seaweed biomass to produce a higher value product. There are also additional considerations surrounding potential environmental and physiological impacts from the bromoform produced by *Asparagopsis*, which is an ozone-depleting organic solvent and probable carcinogen.

The Federal Government has recently directed $9.3 million to scale-up land-based production of *Asparagopsis* including:

- a $3.82 million funding contribution through the Securing Raw Materials Program, which will enable Sea Forest, in collaboration with the University of Tasmania, to develop a commercial-scale, land-based *Asparagopsis* production model. This is in addition to previous funding for Sea Forest including

$1 million through the Entrepreneurs' Programme and $675,000 from the Commercialisation Fund for *Asparagopsis armata*.

- a $3.76 million funding contribution through the Securing Raw Materials Program for CH4 South Australia's land-based seaweed production project in regional South Australia.

On the other hand, there is little published information regarding ocean farming, with no literature reporting attempts or success planting hatchery-reared seedlings into the ocean. There are two papers which detail techniques for *Asparagopsis* farming in the ocean, both of which focussed on *A. armata*, and used fragments of wild harvested plants transplanted to lines deployed on ocean farms in Ireland and Australia (Kraan and Barrington 2005, Wright et al. 2022). While these studies offer ideas for farming techniques and substrates, as well as highlighting the feasibility of mariculture, the wild-harvest model is unlikely to be considered as a sustainable solution by permitting authorities around Australia. In fact, survey results from the Tasmanian Government stated 'There is still a need for wild collected seed stock, [but] Government does not intend to continue to enable this activity'. It is, therefore, likely that deploying ropes that are inoculated with spores reared in the hatchery will be the most viable way to farm *Asparagopsis* in the ocean.

Central and South-East Asia are well known as the home of seaweed production, with the majority of the world's seaweed coming from just a few Asian countries. The Australian Centre for International Agricultural Research was contacted as they were participating in several seaweed related collaborations in Asia. ACIAR reported that they had scoped the potential for *Asparagopsis* work in SE Asia but concluded that 'the level of sophistication of production methods and processing was such that it excluded the smallholders ACIAR is interested in benefitting', but they are hoping with time that the sector will develop.

3.5 Processing/Manufacture of products (harvest and processing)

Once seaweed has grown at sea, or tanks have increased to capacity, the biomass must be harvested and prepared for processing into final products. The main product of interest for *Asparagopsis* biomass is as a feed supplement for methane reduction, and so far, processing and handling research has centred around products which retain bromoform, whilst still being palatable to cattle and practical to transport. At present the development of other products utilising *Asparagopsis* is limited; however, it is well known that there is a diverse array of medicinal benefits for the use of *Asparagopsis* (Haslin et al. 2001, Ponte et al. 2022). This section details existing knowledge regarding harvesting, handling, processing into a product, and storage and transport.

Little published information is available regarding the process of harvesting, and with no companies currently producing commercial quantities, there have been few opportunities to develop harvest protocols. It is well known that *Asparagopsis* stores bromoform in specialised sacks within its cells for release as a defence mechanism (Paul et al. 2006). This means that when stressed or damaged the plant will release the bromoform, either reducing its efficacy or rendering it useless for cattle feed. It is well accepted that handling is important, but despite this, there is no publicly available best-practice information regarding bromoform release or degradation rates, handling practices, exposure to air, or processing activities which may result in loss of bromoform.

There is a distinct lack of detail around the dewatering process for *Asparagopsis* at harvest, either in the tetrasporophyte or gametophyte form. A range of techniques have been used to dewater plants, from patting dry, to using salad spinners and domestic washing machines and centrifuges. Each of these methods removes varying amounts of water but no comparisons have been made between these to determine which is the most suitable. Indeed, the level of water that can be retained in harvested *Asparagopsis* prior to processing has not been defined.

In addition, the wet weight:dry weight (ww:dw) conversion rate, or the amount of water retained by *Asparagopsis* biomass, is vital to standardise reported growth rates, stocking densities, production rates, bromoform concentrations and end product utilisation. Only one paper was uncovered that reported their wet:dry conversion results (Schuenhoff et al. 2006), who found a rate of 1:0.25 centrifuged wet weight to dry weight. These authors also detailed their technique for dewatering and the technology used, as well as their method for measuring dry weight. Limited papers report their dewatering techniques prior to weighing. There are no cases where papers report ash-free dry weight, or freeze-dried weight conversion factors. This makes comparisons between studies impossible and adds further subjectivity to reported growth rates and bromoform concentrations.

Initially all samples for cattle feed trials were freeze dried to maintain active compounds (Vucko et al. 2017), and papers reported weights and concentrations based on this technique. This is still widely used but more recently there have been several papers which detail alternative ways of processing *Asparagopsis* to retain bromoform. One emerging technique is to submerge the seaweed in oil; however, there are discrepancies in the literature around types of oil, concentrations, steeping times and storage conditions (Magnusson et al. 2020, Tan et al. 2023). It is also important to understand how bromoform concentrations may be converted for comparison between the different products being developed. There is also one patent which protects the use of *Asparagopsis* steeped in oil as a feed for cattle, and this is currently owned by FutureFeed.

Storage and shelf life is another area lacking research and publicly available information. It is believed that freeze-dried products need to be stored in very specific conditions to prevent bromoform loss (Regal et al. 2020) while oil products are more stable (Magnusson et al. 2020, Tan et al. 2023). However, the discrepancies in data and the lack of replication indicate a need for focussed research in this area.

FutureFeed are the IP holders for *Asparagopsis* cattle feed products and they undertake research and development into certification, standards, regulation and marketing for *Asparagopsis* feed. They also state that they ensure growers comply with standards developed by the industry and therefore it is believed that the majority of information regarding processing and handling is managed within their group and made available to all licenced growers.

3.6 Products and product development

Currently, the main demand for *Asparagopsis* biomass is as a cattle feed supplement for methane reduction; however, it is important to note the medical and pharmaceutical potential of this species. There are also patents which detail the immune benefits when *Asparagopsis* is incorporated into a feed supplement for farmed fish.

There are several publications which introduce the pharmaceutical properties of *Asparagopsis* (Haslin et al. 2001, Genovese et al. 2009, Nunes et al. 2018, Ponte et al. 2022), as well as a significant number of cosmetic and pharmaceutical patents regarding the use of *Asparagopsis*. Ponte et al. (2022) reported that *Asparagopsis* has been tested for antioxidant, antibacterial, antifungal, antiviral, antifouling, cytotoxic and enzyme-inhibitory activity but found that these were minimal and further research was recommended. There are 22 patents that protect the use *Asparagopsis* for pharmaceutical purposes, including acne treatment, skin whitening, body and hair wash, and traditional medicine.

In the past three years *Asparagopsis* has gained considerable media attention for its potential to reduce methane emissions in ruminant animals, with cows being considered the highest emitting livestock. Kinley et al. (2016) published the first record of methane reduction in cows, where an inclusion of 2% *Asparagopsis* in the diet resulted in an almost 100% reduction in methane emissions. Since this time, there have been at least a further 11 papers testing different feed rates, the health implications to cattle, *in vivo* (Roque et al. 2019b) and *in vitro* application (Machado et al. 2018), as well as a feed supplement for sheep (Li et al. 2018, Roque et al. 2019a, 2021, Kinley et al. 2022, Alvarez-Hess et al. 2023). There is a high level of variability in reported emissions reductions (Roque et al. 2019b), often linked to variability in feeding rates, and this indicates a necessity for further research (Kinley et al. 2021). There also remains concerns for the health of the animals, and the potential for bromoform and other chemicals (e.g. iodine) to pass into the meat or milk, which will require further research (Muizelaar et al. 2021, Glasson et al. 2022). A considerable number of these works have been completed by (or through collaboration with) FutureFeed. They have ongoing research programs investigating product development and are considered the leading organisation managing research within this aspect of the supply chain.

A three stage Methane Emissions Reduction in Livestock (MERiL) program has been initiated by the Australian Government Department of Climate Change, Energy, the Environment and Water. This program incorporates a significant number of government agencies, private enterprises, universities and research institutions. Nearly $30 million of funding has been allocated for research into feasibility, productivity, approach consistency, evaluation and framework development, delivery technologies, and validation of low emissions feed technology. A significant portion of this investment has gone into *Asparagopsis* feed trials and product development across industry and researchers. Securing the volumes needed to support trials has proven challenging according to some stakeholders and this further highlights the major gap around the supply side of the industry. By contrast, one grower reported excess volumes in storage due to a significant reduction in trial size by a project.

4 Stakeholder survey responses

A total of eighteen stakeholders were contacted, representing groups from industry, government research agencies, and universities. All groups had either seaweed farming experience or were undertaking phycological research, with most working directly on *Asparagopsis*. At the time of writing, ten surveys, five formal interviews and ten discussions were completed. Of the ten surveys received, eight were from private industry, and two from government organisations. Two stakeholders were not available during the time frame. Of the ten ASSA members contacted, six responded either through interview or survey. Several of the ASSA members who did not respond are focussed on seaweed species other than *Asparagopsis* so this is not unexpected. One relevant company began the survey but did not complete the majority of questions and then declined to comment in interview. One relevant company provided a discussion but did not provide a survey response.

4.1 Industry development status

The initial few questions in the survey were targeted at gathering baseline information regarding the current status of the stakeholders' activities including collaborations, farm establishment and licencing. During all interviews the stakeholders were encouraged to discuss their farms/facilities and their progress to date.

Of the surveyed growers, two stakeholders were focused only on land-based farming, three were working on both land and ocean farming, and the other three were mainly focussed on mariculture but had established land-based hatchery facilities (Figure 5). The stakeholders focussed on mariculture indicated the size of their ocean leases, which varied considerably in size from 32 to 700Ha and one group with small research plots. TASNRE indicated one lease in Tasmania was 1600 ha in size. Six of the respondents indicated that they are working with both species, *A. taxiformis* and *A. armata*, with two focussed solely on *A. taxiformis*. Thus, neither species was highlighted as a priority over the other, and providing support for both farming techniques (land and ocean) is equally important.

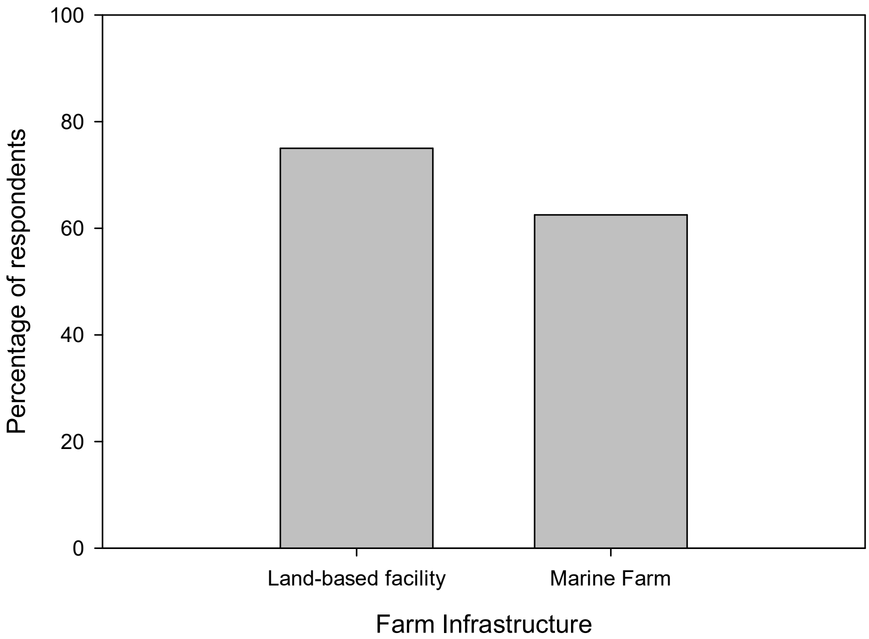

Figure 5 Proportion of respondents focussing on land-based farming or mariculture. Results are presented as a percentage of eight responses received, in some cases stakeholders indicated having both land- and marine-based farms.

Four of the respondents indicated that they were licenced by FutureFeed to sell *Asparagopsis* while three were not, and one was currently seeking a licence. There are currently five Australian companies who are licensed by FutureFeed, and all were contacted. All eight respondents said that they are collaborating with external organisations, and this included a mix of universities and industry collaboration, with one respondent indicating that they could not disclose their collaboration.

When asked about the progress of their research in terms of phenology and lifecycle, four groups selected that they were in the early stages or their research, two selected medium, and one advanced. The final group did indicate that they were commercially cultivating both species of *Asparagopsis* from laboratory reared seedlings (Figure 6). One respondent provided extensive detail on this topic saying that they were yet to achieve commercial cultivation because 'further refinements to the hatchery and nursery cultivation methodologies are still required to stabilize production outcomes'. These respondents said they had completed hundreds of controlled experiments over more than four years and still needed to intensify their R&D work to improve the consistency and quality of seeded material for deployment.

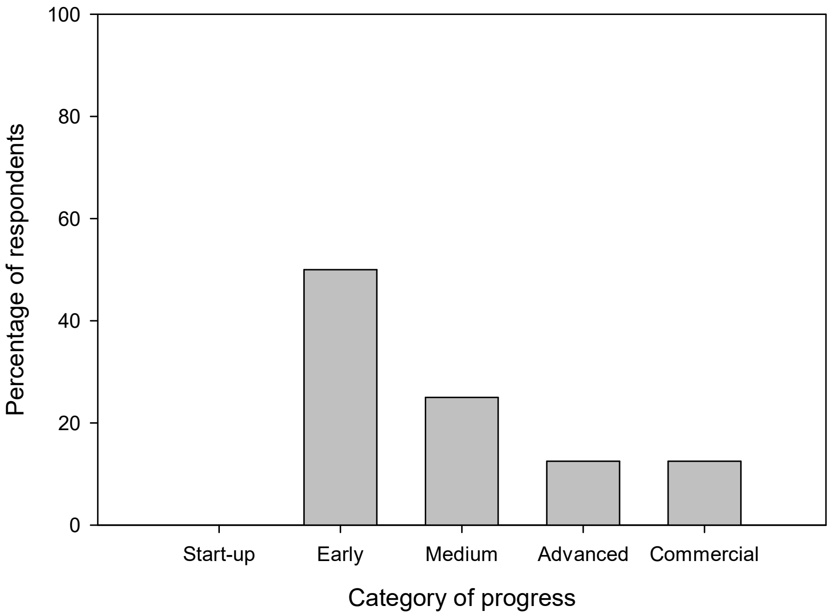

Figure 6 Surveyed stakeholders were asked to select an option indicating their research status by answering the question 'How advanced do you assess your company to be in the development of *Asparagopsis* phenology, lifecycle closure and hatchery techniques?'. Answer choices for research status were; Start Up – we have progressed some cultivation using vegetative methods, Early – we have researchers who know how to get spores to grow to tetrasporophyte stage, Medium – we can get tetrasporophytes reproducing in laboratory conditions but have had limited success/not advanced to seeding to substrates, Advanced – we are successfully cultivating *Asparagopsis* seaweed already, and Commercial – cultivating *Asparagopsis* from laboratory grown seedlings either in tanks or mariculture. Results are presented as a percentage of eight responses received.

4.2 Major challenges

When asked about future obstacles for the NHN all respondents highlighted IP conflicts and collaborations as being the biggest challenges. Respondents included an unwillingness to share knowledge, conflicts of interest and a lack of collaboration as concerns. One company with over four years dedicated *Asparagopsis* research stated that;

> *"conflict of interests between the different companies and a "false perception of success" when start-ups report tetrasporogenesis, which in itself is not a particularly meaningful accomplishment. From our long experience, triggering sporogenesis is not the primary challenge and is just one of many steps along the path to success. Substantial fundamental research is required before establishing a commercially focused NHN".*

Despite the anticipated lack of collaboration, all of the respondents indicated that they would be happy to contribute to a biological database including information on genetics, location data, growth habits, tolerances, and bromoform content. This enthusiasm for sharing is likely biased by the fact that only those stakeholders willing to share information were willing to complete the survey.

There were various other challenges that the stakeholders had faced and were happy to share in the survey, which may pose obstacles in the future for the NHN. All challenges identified by stakeholders are listed in Table 4.

Table 4 List of responses to questions regarding major challenges faced and potential challenged for the NHN. All wording and terminology are taken directly from survey responses

Stakeholder predicted or encountered challenges
IP and Knowledge Sharing
- Sharing of knowledge
- Collaboration and knowledge sharing
- Sharing of IP that creates value for existing operators
- Unwillingness to share knowledge due to IP and company policies
- Conflict of interests between the different companies
- IP negotiations and access to prior research
Funding
- Investment to hire a team to work on the project (two responses)
- Access to funds to speed up the research and pilot plant to commercial scale trials
Lack of Knowledge
- Knowledge of techniques is not established / available
- False perception of success
- Inducing sexual reproduction
- Access to seeded substrate
- Culture stock collection
Consistency
- Creating consistent standards / regulations
- Achieving consistent results and high-quality material especially in ‘more difficult’ strains
Contamination
- Land-based infection control
- Contamination of cultures
- Red algae contamination in *Asparagopsis* cultures
Regulatory
- Aquaculture lease approval
- Consistency of State Government Legislation for operations
Risks associated with translocation of seaweeds (disease and genetic)
Slow growth - conditions still need to be optimised at all scales
Seasonality of farming and accessibility to ‘year-round’ farming

The MBCRC have gathered considerable funding for research with industry partners including Sea Forest and CH4 Global. The MBCRC is working with some companies and undertaking significant projects focussing on aspects of cultivation and production refinement as directed by industry partners. However, it was clearly explained that information regarding *Asparagopsis* production is considered proprietary and remains the property of the companies providing the funding to each MBCRC project. In one case it was stated that there have been smaller companies asking the committed universities for help with farming, but they can't utilise their researchers for projects outside the MBCRC. The MBCRC suggest the major knowledge gaps are diseases, regional genetics, biosecurity, and governance. The MBCRC does not consider hatchery and cultivation research to be a priority as it is already being addressed by the two bigger seaweed companies who are participants in the MBCRC. This highlights that knowledge sharing of research outcomes continues to be a major challenge for the *Asparagopsis* industry. Therefore, there is an opportunity and need for the Australian Sustainable Seaweed Alliance (ASSA) to lead key industry development projects so that it can make these research outcomes available to broader industry.

4.3 *Asparagopsis* R&D gaps and needs assessment

Survey questions regarding other knowledge gaps and priorities for the seaweed industry as a whole provided a bigger picture of research requirements for *Asparagopsis* (Table 5) and can be used to help focus the direction of the NHN. There were a range of responses, over a range of topics, and these largely depended on the focus of the cultivation being undertaken by the organisation i.e. land based or mariculture. Both species, and both farming techniques, were equally represented by the survey respondents, highlighting the need for the NHN to provide unbiased support for all farm types.

Table 5 List of identified knowledge gaps highlighted by stakeholders sorted by supply chain element. All wording and terminology are taken directly from survey responses

Knowledge gap
Wild Population Assessment
- Wild population species mapping (key regions, Tasmania and South Australia underway)
- Broodstock selection
- Understanding the seasonal, locational, genetic, microbiome and environmental variations in the natural production cycles
- Identification of most suitable geographies for ocean based *Asparagopsis* farming, including methods for identifying ideal farming sites considering environmental, oceanographic and other factors
Hatchery
- Hatchery techniques from spore to germling
- Life cycle management

- How to successfully set up *Asparagopsis* hatchery
- Consistent supply of seeded substrate
- Clean culture development and management/Contamination
- Achieving more consistency and predictability in spore quality and viability and in spores/seedlings retention on the seeded material

Cultivation

- Ongrowing on land and in the sea
- Adaptation of photobioreactor technology to fast-track inoculum production
- What are the best methodologies to scale up
- Ability to grow *Asparagopsis* at scale and commercial feasibility

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When asked directly what they thought the role and priorities of the NHN were, stakeholder responses were extensive and varied (Table 6). Most respondents recommended that that the NHN should focus on sharing knowledge that can help companies with the successful culture of *Asparagopsis*, and this included unlocking technical knowledge and expertise, creating seeded substrates and seedlings, managing contamination, hatchery design and technology, and selective breeding. The sharing of knowledge regarding scale up techniques for both land-based farming and mariculture was also highlighted.

Table 6 Priority activities for the National Hatchery Network as identified by stakeholders. All wording and terminology are taken directly from survey responses

Priorities for *Asparagopsis* R&D
Wild Population Assessment
Phenology and genetics for each location where mariculture is or will soon be approved
Distribution of species
Hatchery
Lifecycle closure, spore induction, collection and cultivation (two responses)
Production techniques for reliable, clean production of germlings for out planting
Propagation excellence
Selective breeding; Identify the best *Asparagopsis* strains for culture conditions and bromoform extraction (two responses)
Identification of suitable hatchery locations (two responses)
Development of hatchery infrastructure, design guide and operation manual (several responses)
Hatchery set-up (temperature, light, nutrients)
Clean culture development and management/Contamination
Cultivation
Share knowledge that can help companies with the successful culture of *Asparagopsis*
Adaptation of photobioreactor technology to fast-track inoculum production

Nutrient removal capabilities

Governance/Other

Distribution of funds to existing operators (one response)

Unlocking the IP negotiations and collaboration; sharing knowledge (three responses)

Creation of a seeded substrate offtake agreement

Translocation restrictions between jurisdictions, biosecurity and responsible practices (two responses)

A significant proportion of respondents were members of ASSA, showing their willingness to collaborate on the NHN.

PRIORITY: Share existing and new knowledge, IP and know-how through training, workshops, handbooks/guides and meetings

Wild population assessment

Ocean farmers highlighted the importance of identifying suitable geographies for mariculture, including methods for identifying ideal farming sites considering environmental, oceanographic and other factors. Understanding seasonality was also mentioned as a research priority for the National Hatchery Network. In fact, the impact of season and growing conditions on bromoform concentrations was mentioned by multiple respondents as an R&D priority for the industry. Since seasonality will vary considerably around Australia, and the extent of *Asparagopsis* growers spans most of the country, it is unlikely that having the NHN focus on dedicated seasonality studies would be of benefit to the industry as a whole. The process of mapping seasonality also takes a minimum of one year to determine, and really requires multiple years to determine if patterns are similar or vary from year to year. This information would be very laborious and would only help farmers in specific regions where the work was undertaken, leaving other groups without support. Instead, the NHN would be best placed to devise standardised techniques for identifying populations, monitoring seasonality and measuring growth and bromoform concentrations. The NHN could maintain a database of all records and this information could be provided to farmers, along with additional support and guidance if required, so that farmers can undertake their own monitoring. The collection of broodstock will also be a significant priority for the NHN, as without culture material no research can be undertaken. Since there are no published techniques for broodstock collection, these will need to be developed and shared with growers.

PRIORITY: Develop protocols for identifying wild populations, collecting broodstock and monitoring seasonality and maintain a database of all records

Several respondents, including the MBCRC, highlighted biosecurity and translocation challenges as being a priority for the NHN. Understanding regional genetics should be a requirement for translocation of *Asparagopsis* from hatcheries to farms, and even for the process of relocating wild plants from the reef to ocean leases. As an example, a recent study investigating the genetic structure of *Ecklonia radiata* kelp in New Zealand recommends that plants not be translocated outside their area of origin, and moving plants could introduce locally absent genotypes to local sub-populations (Nepper-Davidsen et al. 2021). Decisions regarding translocation will be reliant on region specific governance, which may vary from state to state, and will need to be strictly adhered to by the NHN. Thus, the NHN will have to prioritise managing these guidelines for each grower, but can also assist in the development of state governance by sharing research findings and developing a genetics bank for all broodstock maintained within the facility.

PRIORITY: Disseminate research findings and genetic data for development of government translocation regulations

Hatchery

Seeded substrates were a major topic of discussion within groups more focused on mariculture. Access to consistent supply of seeded substrate for ocean deployment was a goal for many surveyed. Despite this being listed as a research priority only three respondents expressed interest in purchasing seeded substrates from the NHN, with two noting that this would only be initially until they developed their own hatchery. The other five said they were not interested in accessing seeded substrate, but sought support to establish their own hatchery. Without available techniques for spore production and substrate seeding, the provision of seeded substrates cannot be undertaken; thus, it should be a priority for the NHN to master the life cycle of both species of *Asparagopsis* and develop techniques for seeding and farm deployment.

PRIORITY: Focussed research to close the life cycle, produce spores and seedlings on demand
PRIORITY: Develop techniques for seeding substrates, growing seedlings for deployment, and transport of seedlings to cultivation sites

Consistency of product was repeatedly mentioned across many surveys and interviews including addressing key technical bottlenecks to improve seedling survivorship, replicability and reliability. One company explained that it takes rigorous testing of methodologies to achieve consistent results with a range of strains, placing particular emphasis on ‘more difficult’ strains. This is also linked to the problem of contamination of cultures, which was highlighted by several respondents. One respondent expressed interest in finding solutions to contamination and suggested a back-up repository for broodstock or a safe store of clean cultures. They also stated that they believed that having access to clean broodstock would really benefit new starters; thus, maintaining monospecific cultures of both life stages of both *Asparagopsis* species from a range of regions would be a of benefit to the NHN.

PRIORITY: Optimise seeding techniques to achieve consistent, replicable and reliable seed stock for farmers
PRIORITY: Develop contamination management techniques
PRIORITY: Maintain clean broodstock repository for all growers participating in the NHN

The process of establishing a hatchery was considered relevant for stakeholders both interested in land-based farming, through inshore tetrasporophyte cultivation, and mariculture through a hatchery for seeding marine leases. Overall interest was expressed in various aspects of how-to set-up and scale-up an *Asparagopsis* hatchery. Topics around hatchery location, establishment protocols, ideal infrastructure and tank design, optimal conditions, and biosecurity were highlighted as priorities. The lack of publicly available literature regarding hatchery set-up also supports this as a priority for the NHN. Operational support was recorded as a knowledge gap through a lack of available expertise, and this is another area where the NHN could offer assistance through training, sharing of knowledge and research findings and potentially licencing technology developed through the establishment of the NHN.

PRIORITY: Develop hatchery technology and infrastructure through experimentation
PRIORITY: Make expertise available by drafting and sharing hatchery design guide, operation manual and standard operating procedures

Stakeholders were asked directly what they saw the role of selective breeding in the future of *Asparagopsis* farming. The definition of a selective breeding program has remained unclear, and there seems to be a wide range of variability across the industry as to what this means for *Asparagopsis* farming. This was also clearly demonstrated in the range of responses to the survey question. One stakeholder thought it would be useful for new-starters, while another suggested it is a much longer-term goal, with a 5-10 year focus. With optimisation and consistency being a hot topic for responses, it seems that selective breeding should be a focus, with one respondent stating that they have undertaken a large, multi-year effort directed at identifying high-performance cultivars. Selective breeding is still very new to the field of seaweed farming, with the first steps only now being undertaken for species with a much more detailed understanding of farming techniques e.g. kelp. Further, the ARC Research Hub for Supercharging Tropical Industry Aquaculture through genetic solutions is focussed on strain selection suggesting this may not be a priority for the NHN in the first two years.

The Tasmanian Department of Natural Resources and Environment has focussed efforts on understanding the potential impacts and risks involved with translocation of *Asparagopsis* around the state. So far, NRETAS have discovered two independent strains of *A. armata* along the coast of Tasmania and plan to further their understanding of dynamics before translocation will be permitted. As was mentioned above, translocation of plants outside of their area of origin should be avoided (Nepper-Davidsen et al. 2021), and as government regulations develop the potential for translocation will become better understood in Australia. For example, seeking out strains with higher bromoform content is not of use if these plants cannot be translocated to farms. Thus, it is unlikely that selective breeding will be an option until there is a better understanding of genetic variability, and so contributing genetic information, and supporting the development of government regulations, should be a higher priority than selective breeding programs.

The NHN will need to adhere to strict biosecurity regulations, which again may vary depending on the state where the hatchery is situated and where broodstock was collected. In such a new field, a NHN for seaweed represents a novel system, meaning that biosecurity practices for a facility like this will require research and development. A number of areas where biosecurity information would be useful includes within the hatchery, within the grow-out facility/area and beyond the hatchery i.e., movements of plants further afield. While there are examples to draw from such as Saltas and the Aquafin CRC, it will be the responsibility of the NHN to develop best practices for *Asparagopsis* according to farmers' requirements and state governance. The Department of Agriculture and Fisheries and the FRDC have also raised concerns about the risks associated with biosecurity, highlighting the significance of translocation research as a priority for the NHN. Therefore, research into the development of biosecurity management practices and technologies should be a high priority, and providing this information to farmers and governments will help support the industry as a whole.

PRIORITY: Research collaborations to develop biosecurity protocols for internal handling of cultures and transport/translocation of broodstock and seeded material

Bromoform improvement was consistently highlighted as a priority by many respondents, and it would be beneficial for the NHN to allocate some research time to this topic. However, bromoform optimisation through selective breeding will not be an option until government regulations are in place for translocation. There is potential for techniques to be developed to increase bromoform during farming; however, these will likely form part of commercial scale cultivation and harvesting and processing aspects of the supply chain, so it is unlikely that it would be a priority for the NHN at this time. However, handling and transport practices for better health and success of broodstock and seedlings will be an important part of the hatchery process, and this will also include maintaining bromoform concentrations. For example, if plants are not handled carefully during transport, or not acclimated prior to deployment, the health of seeded substrates or broodstock could suffer, resulting in reduced growth and bromoform production.

PRIORITY: Research quality assurance practices for all stages of the hatchery process to maintain and improve health of seed stock provided to farmers

Cultivation

While it would be reasonable to assume that the NHN scope would not extend beyond the hatchery aspects of *Asparagopsis* farming, it is vital that researchers are involved further downstream into the cultivation process. The most important reason for this involvement is to ensure the success of material provided from the hatchery. Seeded lines, or broodstock, provided to growers will need to be tailored to a range of situations such as season, site specifics, infrastructure types, handling, and other intricacies of scaled cultivation. The success of the NHN will be indicated by an increase in cultivation. This is therefore reliant on sharing of field results through onsite visits/support and the reporting of production data. There is also a likelihood that growers will be eager to develop their own ocean growing and land-based farming techniques and may want seed material to be tailored for their technology in future.

PRIORITY: Operational support and field advice for the successful grow-out of provided seed, *in situ* monitoring of deployments, and transparent reporting of production results by growers

It is clear from the surveys and interviews that some believe it is not possible to achieve reliable and consistent production in the short time the industry has been in existence; and this is also indicated by the limited commercial product available in the market. Surveys identified a lack of scale-up and commercial know-how as being a major concern. This includes seaweed farm design and engineering, equipment availability and workforce capability for large scale farming. Research needs include information sharing across industry on new and emerging techniques, design, technology and equipment which will likely develop through the scale-up of cultivation but it presents an opportunity for collaboration and industry development support. While engineering and infrastructure technology may be translatable from other aquaculture or fisheries sectors there is a need for workforce development to support the growing industry in key regions.

PRIORITY: Share emerging scale-up knowledge, research findings and technology available for cultivation stage
PRIORITY: Assist growers to access technology collectively where possible e.g. engineering design
PRIORITY: Workforce development for the seaweed industry

Despite only being mentioned by one stakeholder, reducing the unit production costs are a high priority for commercialisation of *Asparagopsis*. This was also alluded to in the response of a second stakeholder who identified the trade-off between scale-up and growth rate needing to be addressed for commercial production. The 2022 AgriFutures Australia report investigating the capital requirements for *Asparagopsis* production also highlighted the importance of research into the economics of farming. This report noted that 'there is no large-scale commercial farming of *Asparagopsis* species from which to derive data, nor any substantial modelling of datasets, benefit-cost analysis or gross margin analysis (Ball et al. 2022). It is important that research is carried out to reduce the costs of production and optimisation of techniques for hatchery, cultivation and product processing for the benefit of the entire industry and customers. This also relates to the comments made by several stakeholders that optimising bromoform concentration was considered a priority, and production cost and product quality will be dependent on these findings. In short, the *Asparagopsis* industry will not be self-sustaining if production costs are inhibitive.

PRIORITY: Supply chain production cost analysis and benchmarking

Processing and product development

Processing and product development were not mentioned in any survey responses or interviews with stakeholders, either as challenges, knowledge gaps or priorities for the NHN. Despite there being a clear lack of publicly available literature regarding harvest and processing, no stakeholder felt this was a priority. In many cases, farmers have already entered into arrangements with cattle farmers to undertake research, but most importantly this is seen as the responsibility of FutureFeed as the global licence holder for the product. FutureFeed is an organisation dedicated to 'research and development; certification and standards, providing regulatory pathways and marketing' for *Asparagopsis* feed (Source: FutureFeed; future-feed.com). FutureFeed are responsible for ensuring their licensed growers comply with standards; thus, it is assumed that all processing and handling standards and product development will be managed by FutureFeed.

Significant Federal Government investment has gone into product trials through the Livestock Emissions Reduction Program; however, until there is an Emissions Reduction Methodology for livestock methane reduction in Australia then there will be a significant barrier to adoption of this technology by customers. One stakeholder indicated that the lack of differentiation of *Asparagopsis* from other competing methane reduction technologies is a market barrier and opportunity that should be considered by FutureFeed as the global license holder.

Around 95% of Australia's beef cattle are farmed through grazing practices so product development specifically for grazing animals has been identified and is being targeted by the Federal Government. A product, which can be provided to grazing animals, would unlock significant market opportunity; however, this needs to be supported by a carbon emissions reduction methodology and policy to support customer uptake.

PRIORITY: Contribute to a Carbon Emissions Reduction methodology

5 Conclusions

This review has highlighted significant knowledge gaps across the supply chain, particularly regarding the hatchery and cultivation processes for *Asparagopsis*, and this is supported by surveys and interviews of major *Asparagopsis* farmers and researchers around Australia. It has been explicitly stated that there is no information available for new starters, and it is clear that many companies are struggling with the same problems, especially in the early start-up stages. The assessment of available knowledge and literature showed that there is no detailed information available regarding the hatchery processes, apart from some literature for spore induction; and, germination, seedling growth, seed attachment and out-planting techniques remain unknown. There are also a lot of methodological gaps around locating and collecting wild populations, and commercial cultivation techniques. This is reinforced by the results of the surveys, with stakeholders highlighting hatchery techniques as being their biggest knowledge gap. Surveys also highlighted gaps in wild population mapping, productivity and site selection, and many identified a lack of scale-up and commercial know-how as being a major concern. Neither species was highlighted as a priority over the other, and providing support for both farming techniques (land and ocean) was considered equally important. In fact, the 2022 AgriFutures Australia report stated that 'The *Asparagopsis* value chain is very much in its infancy. Even basic questions – such as whether terrestrial cultivation systems will prove more productive and profitable than ocean-based systems – are some years from being answered' (Ball et al. 2022).

Considering those gaps which received most consistent comment in the surveys and interviews, and the investment already committed through R&D funding sources in Australia, the NHN should focus on broodstock collection advice, hatchery design and technology optimisation, hatchery protocols and seeding techniques to provide consistent, clean cultures of *Asparagopsis.* This can be achieved through a rigorous research program, workforce development, sharing of knowledge, training programs for growers and on-site support and advice. The full list of priorities is presented in (Table 7). The NHN needs to consider providing support to existing growers to achieve consistent production and will work closely with companies and research partners that have indicated they are willing to collaborate on *Asparagopsis* hatchery R&D. The National Hatchery Network Implementation Plan will outline the approach to address the priorities identified in this report.

Table 7 List of *Asparagopsis* R&D priorities for the NHN identified through the review and surveys undertaken in this report

***Asparagopsis* R&D priorities according to supply chain element**
- Share existing and new knowledge, IP and know-how through training, workshops, handbooks/guides and meetings
Wild Population Assessment

- Develop protocols for identifying wild populations, collecting broodstock and monitoring seasonality and maintain a database of all records
- Disseminate research findings and genetic data for development of government translocation regulations

Hatchery

- Focussed research to close the life cycle, produce spores and seedlings on demand
- Develop techniques for seeding substrates, growing seedlings for deployment, and transport of seedlings to cultivation sites
- Optimise seeding techniques to achieve consistent, replicable and reliable seed stock for farmers
- Develop contamination management techniques
- Maintain clean broodstock repository for all growers participating in the NHN
- Develop hatchery technology and infrastructure through experimentation
- Make expertise available by drafting and sharing hatchery design guide, operation manual and standard operating procedures
- Research collaborations to develop biosecurity protocols for internal handling of cultures and transport/translocation of broodstock and seeded material
- Research quality assurance practices for all stages of the hatchery process to maintain and improve health of seed stock provided to farmers

Cultivation

- Operational support and field advice for the successful grow-out of provided seed, *in situ* monitoring of deployments, and transparent reporting of production results by growers
- Share emerging scale-up knowledge, research findings and technology available for cultivation stage
- Assist growers to access technology collectively where possible e.g. engineering design
- Workforce development for the seaweed industry
- Supply chain production cost analysis and benchmarking

Processing and Product Development

- Contribute to a Carbon Emissions Reduction methodology

It was also identified that it would be beneficial to develop a national database of natural variability and production parameters of wild populations as this will vary between locations and strains. Information such as seasonal occurrence of species and life stages, habitat identification and genetic structure will also assist state governments with evolving biosecurity management practices that need to be established in parallel. While some work is underway in Tasmania and South Australia, similar projects will be needed in Queensland, Western Australia and Victoria to support those industry participants.

Overall, the emerging seaweed industry would benefit from greater sharing of research findings and emerging technologies across participants in the sector. A focus on workforce capability development, as well as policy development to support production and product uptake in Australia would fast-track the growth of the *Asparagopsis* seaweed sector. Many of the advances made by the NHN for *Asparagopsis* will also provide a useful model for the farming of other seaweed species in Australia.

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Appendix A – R&D landscape

Summary of papers and projects related to Asparagopsis

R&D Project Name	Supply Chain Element	Who	Association	Funded by	Funding	Status	Summary
Methane Emissions Reduction in Livestock (MERiL) Stage 1	Product Development	Bovine dynamics/Sea Forest/Stockyard Feedlot		DCCEEW	$1,000,000	December 2024 (2.5 years from start)	Trials the use of the *Asparagopsis* in a large-scale commercial feedlot for Angus beef, to understand its impacts on emissions and productivity including meat quality
Methane Emissions Reduction in Livestock (MERiL) Stage 1	Product Development	FutureFeed/MLA/UNE/ Australian Country Choice Holdings/Woolworths/Corporate Carbon Advisory/GrainCorp/Bovine Dynamics		DCCEEW	$500,000	December 2024 (2.5 years from start)	Tests *Asparagopsis* seaweed in beef cattle in the University of New England's Tullimba feedlot
Methane Emissions Reduction in Livestock (MERiL) Stage 1	Product Development	UNE/Australian Wool Innovation/Sea Forest		DCCEEW	$500,000	December 2024 (2.5 years from start)	Trials the use of *Asparagopsis* seaweed in sheep in northern New South Wales
Methane Emissions Reduction in Livestock (MERiL) Stage 1	Product Development	GrainCorp/Agriculture Victoria/Future Feed/Australian Lot Feeders Association/Midfield Meat		DCCEEW	$500,000	December 2024 (2.5 years from start)	Laboratory trials to test *Asparagopsis* seaweed stability in livestock feed and on-field trials to determine methane emission reductions in livestock

R&D Project Name	Supply Chain Element	Who	Association	Funded by	Funding	Status	Summary
		International/Bovine Dynamics					
Methane Emissions Reduction in Livestock (MERiL) Stage 2: Feasibility and Development Grants	Product Development	Sea Forest/Dickson Ag/Ruminati/Australian Agricultural Company/Tasmanian Department of Primary Industries		DCCEEW	$383,657	June 2023	Development of products containing *Asparagopsis* oil for grazing systems
Methane Emissions Reduction in Livestock (MERiL)Stage 3: Validation and Demonstration Round 1	Product Development	Graincorp/FutureFeed/University of Queensland/Agriculture Victoria Services			$2,932,438	April 2025	Undertake large-scale dairy and beef livestock grazing trials to demonstrate the use of the seaweed *Asparagopsis* as a low-emission feed supplement
Methane Emissions Reduction in Livestock (MERiL)Stage 3: Validation and Demonstration Round 1	Product Development	University of Adelaide/CH4/ASSA/Mackillop Farm Management Group/Barossa Improved Grazing Group/SA Livestock Consultants			$1,075,601	April 2025	Investigate feeding seaweed supplements to pregnant cows and its long-term effect on methane production in their progeny

R&D Project Name	Supply Chain Element	Who	Association	Funded by	Funding	Status	Summary
Methane Emissions Reduction in Livestock (MERiL)Stage 3: Validation and Demonstration Round 1	Product Development	UNE/DPI South Australia/UWA/Feedworks/Australian Wool Innovation			$1,954,690	April 2025	To evaluate 2 automated feeders for methane-reducing supplements – *Asparagopsis*, Bovaer and Agolin – to sheep
Securing Raw Materials Program	Cultivation	Sea Forest/UTAS	UTAS	DCCEEW	$3,820,000	31st March 2022	Develop a commercial-scale, land-based *Asparagopsis* production model
Securing Raw Materials Program	Cultivation	CH4 South Australia		DCCEEW	$3,760,000	31st March 2022	Seaweed production project in regional South Australia
Entrepreneurs' Programme	Cultivation	Sea Forest		DCCEEW	$1,000,000		Develop a commercial-scale, land-based *Asparagopsis* production model
Commercialisation Fund	Cultivation	Sea Forest		DCCEEW	$675,000		Develop a commercial-scale, land-based *Asparagopsis* production model
Asparagopsis R&D review and implementation plan for a national seaweed hatchery network	Cultivation	Australian Seaweed Institute		FRDC	$104,800	6 July 2023	Review *Asparagopsis* R&D across the supply chain from production to application

R&D Project Name	Supply Chain Element	Who	Association	Funded by	Funding	Status	Summary
Seaweed biofilters for Great Barrier Reef water quality	Hatchery & Cultivation	Jo Kelly	Australian Seaweed Institute	GBRF	$920,000	To complete June 2024	One PhD student looking at hatchery techniques for *Sargassum* and *Asparagopsis taxiformis* and small scale field trials in reef catchments
Cultivation trials of the red seaweed *Asparagopsis armata* and *A. taxiformis*	Hatchery	Sasi Nayar	University of Adelaide	FRDC; Commercial partner CH4 Global	$553,331	27 August 2020	
Overcoming propagule supply bottlenecks for seaweed production	Hatchery	Manoj Kumar	University of Technology Sydney (UTS)	FRDC	$267,706	30 October 2022	Establish micropropagation techniques for year-round seedstock supply of seaweeds, and demonstrate the commercial practicality of workflow for micropropagation
Developing *Asparagopsis* seaweed cultivation at scale in Northern Australia	Hatchery	John Statton (UWA)/Pilbara Blue Carbon/Immersion Group/Abrolhos Aquaculture Australia/Future Green Solutions/Rangelands NRM	UWA/Curtin	NACRC	$450,000	30th May 2023	Address key knowledge blocks to unlock *Asparagopsis* potential for Northern Australia
Developing *Asparagopsis* cultivation at scale for rapid industry growth	Hatchery	John Statton	UWA	AgriFutures	$399,152	1st February 2023	

R&D Project Name	Supply Chain Element	Who	Association	Funded by	Funding	Status	Summary
The design, planting and monitoring of ponds with seagrass, mangrove and a pilot of red seaweed to explore the potential for carbon sequestration	Cultivation	John Statton	UWA	Pilbara Blue Carbon	$207,370	30th September 2023	
Harnessing seaweed genes to mitigate methane emissions from livestock	Wild Population Assessment	Scott Cummins, Nick Paul, Min Zhao, Alex Campbell, Eiichi Shoguchi	USC	ARC	$448,103	2nd March 2023	Harnessing seaweed genes to mitigate methane emissions from livestock
Research hub for supercharing tropical aquaculture through genetic solutions	Wild Population Assessment	JCU/Seaforest	JCU	ARC	$4,900,000	2021 - 2026	
Capital requirements for commercial production of *Asparagopsis* for methane reduction in cattle	Cultivation	Alex Ball, Scott Williams, Russell Pattinson	Consultants	AgriFutures			

R&D Project Name	Supply Chain Element	Who	Association	Funded by	Funding	Status	Summary
Baseline data to inform a new aquaculture industry: mapping the distribution, abundance and chemical variation in *Asparagopsis armata* around Tasmania (2022 - 2023)	Wild Population Assessment	Catriona Hurd, Jeff Wright, Rocky de Nys R, Masa Tatsumi	UTAS	Marine Bioproducts CRC	$200,000	2023	Undertake targeted surveys for 12 months to determine spatial and temporal patterns of abundance, reproduction and bromoform concentrations in *Asparagopsis* around Tasmania and use molecular tools to determine patterns of genetic structure in *Asparagopsis*.
Accelerating the development of finfish mariculture in Cambodia through south-south research cooperation with Indonesia	Wild Population Assessment	Nick Paul	University of the Sunshine Coast	ACIAR		Completed 2021	Several publications came from this work where *Asparagopsis* was used for fish feed, and it is believed that University of the Sunshine Coast is working in Indonesia in *Asparagopsis*
Greenhouse gas emissions footprint associated with the cultivation of *Asparagopsis*, using a life cycle assessment approach	All Aspects	Alice Jones and Tass Shrestha	University of Adelaide				
Mapping the distribution, abundance and chemical variation in	Wild Population Assessment	Dianne Maynard	Department of Natural Resources				

R&D Project Name	Supply Chain Element	Who	Association	Funded by	Funding	Status	Summary
Asparagopsis armata around Tasmania			and Environment				
Baseline Seaweed Health Project that includes *Asparagopsis armata*	Wild Population Assessment	Dianne Maynard	Department of Natural Resources and Environment				

R&D Project Name	Supply Chain Element	Who	Association	Status	Document type	Output title
A direct comparison of the performance of the seaweed biofilters, *Asparagopsis armata* and *Ulva rigida*	Cultivation	Mata et al.	James Cook University	Completed 2010	Peer-reviewed publication	Journal of Applied Phycology
Carbon/nutrient balance in relation to biomass production and halogenated compound content in red alga *Asparagopsis taxiformis* (Bonnemaisoniaceae)	Cultivation	Mata et al.	James Cook University	Completed 2012	Peer-reviewed publication	Journal of Phycology
Chemical defence against bacteria in the red alga *Asparagopsis armata*: linking structure with function	Cultivation	Paul et al.	University of the Sunshine Coast	Completed 2006	Peer-reviewed publication	Marine Ecology Progress Series
Is the tetrasporophyte of *Asparagopsis armata* (Bonnemaisoniales) limited by inorganic carbon in integrated aquaculture?	Cultivation	Mata et al.	James Cook University	Completed 2007	Peer-reviewed publication	Journal of Phycology
Simple growth patterns can create complex trajectories for the ontogeny of constitutive chemical defences in seaweeds	Cultivation	Paul et al.	James Cook University	Completed 2014	Peer-reviewed publication	PLoS ONE
The effects of light and temperature on the photosynthesis of the *Asparagopsis armata* tetrasporophyte (*Falkenbergia rufolanosa*), cultivated in tanks	Cultivation	Mata et al.	James Cook University	Completed 2006	Peer-reviewed publication	Aquaculture
The tetrasporophyte of *Asparagopsis armata* as a novel seaweed biofilter	Cultivation	Schuenhoff et al.	James Cook University	Completed 2006	Peer-reviewed publication	Aquaculture
Ultrastructure of the gland cells of the red alga *Asparagopsis armata* (Bonnemaisoniaceae)	Cultivation	Paul et al.	University of New South Wales	Completed 2006	Peer-reviewed publication	Journal of Phycology

R&D Project Name	Supply Chain Element	Who	Association	Status	Document type	Output title
Asexual propagation of *Asparagopsis armata* gametophytes: fragmentation, regrowth and attachment mechanisms for sea-based cultivation	Cultivation	Wright et al.	University of Tasmania	Completed 2022	Peer-reviewed publication	Journal of Applied Phycology
Asexual cultivation techniques of the red macroalgae *Asparagopsis taxiformis* for commercial application	Cultivation	Hunter	Curtin University	Completed 2022	Thesis	
Culture medium composition for optimal thallus regeneration in the red alga *Asparagopsis armata* Harvey (Rhodophyta, Bonnemaisoniaceae)	Cultivation	Haslin and Pellegrini	University of the Mediterranean, France	Completed 2001	Peer-reviewed publication	Botanica Marina
Bromoform, mycosporine-like amino acids and phycobiliprotein content and stability in *Asparagopsis armata* during long-term indoor cultivation	Cultivation	Zanolla et al.	National University of Ireland	Completed 2022	Peer-reviewed publication	Journal of Applied Phycology
Commercial cultivation, industrial application, and potential halocarbon biosynthesis pathway of *Asparagopsis* sp.	Cultivation	Zhu et al.	Shandong Agricultural University	Completed 2021	Peer-reviewed publication	Algal Research
Commercial farming of *Asparagopsis armata* (Bonnemaisoniceae, Rhodophyta) in Ireland, maintenance of an introduced species?	Cultivation/Wild Population Assessment	Kraan and Barrington	National University of Ireland	Completed 2005	Peer-reviewed publication	Journal of Applied Phycology
Culture studies on induction of tetraspores and their subsequent development in the red alga *Falkenbergia rufolanosa* (Harvey) Schmitz	Hatchery	Oza	Central Salt and Marine Chemicals Research Institute, India	Completed 1977	Peer-reviewed publication	Botania Marina

R&D Project Name	Supply Chain Element	Who	Association	Status	Document type	Output title
Daylength, temperature and nutrient control of tetrasporogenesis in *Asparagopsis armata* (Rhodophyta)	Hatchery	Guiry and Dawes	National University of Ireland	Completed 1992	Peer-reviewed publication	Journal Of Experimental Marine Biology And Ecology
Reproduction and cultivation of *Asparagopsis taxiformis* (Delile) Trevisan	Hatchery	Batista	Universidade do Algarve	Completed 2020	Thesis	
Scoping study of the capital requirements for commercial production of *Asparagopsis* for methane reduction in cattle	Hatchery/Cultivation	Ball et al.	AgriFutures	Completed 2022	Report	
Image-based analysis and quantification of biofouling in cultures of the red alga *Asparagopsis taxiformis*	Hatchery/Cultivation	Dishon et al.	Scripps Institute of Oceanography	Completed 2022	Peer-reviewed publication	Journal of Applied Phycology
Drying process, storage conditions, and time alter the biochemical composition and bioactivity of the anti-greenhouse seaweed *Asparagopsis taxiformis*	Processing/Manufacture of Products	Regal et al.	Universidade de Lisboa, Portugal	Completed 2020	Peer-reviewed publication	European Food Research and Technology
Exploration of methane mitigation efficacy using *Asparagopsis*-derived bioactives stabilized in edible oil compared to freeze-dried *Asparagopsis* in vitro	Product Development	Kinley et al.	FutureFeed	Completed 2022	Peer-reviewed publication	American Journal of Plant Sciences
In vitro anti-HIV activity of sulfated cell-wall polysaccharides from gametic, carposporic and tetrasporic stages of the Mediterranean red alga *Asparagopsis armata*	Product Development	Haslin et al.	French National Institute for Agriculture, Food and Environment	Completed 2001	Peer-reviewed publication	Planta Medica
Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed	Product Development	Kinley et al.	James Cook University	Completed 2020	Peer-reviewed publication	Journal of Cleaner Production

R&D Project Name	Supply Chain Element	Who	Association	Status	Document type	Output title
Nitrogen uptake kinetics of an enteric methane inhibitor, the red seaweed *Asparagopsis armata*	Cultivation	Torres et al.	Greener Grazing and Centre for Marine Sciences, Portugal	Completed 2021	Peer-reviewed publication	Journal of Applied Phycology
Nutraceutical potential of *Asparagopsis taxiformis* (Delile) Trevisan extracts and assessment of a downstream purification strategy	Product Development	Nunes et al.	University of Madeira, Portugal	Completed 2018	Peer-reviewed publication	Heliyon
Safety and transfer study: Transfer of bromoform present in *Asparagopsis taxiformis* to milk and urine of lactating dairy cows	Product Development	Muizelaar et al.	Wageningen University and Research, Netherlands	Completed 2021	Peer-reviewed publication	Foods
Shelf-life stability of *Asparagopsis* bromoform in oil and freeze-dried powder	Processing/Manufacture of Products	Tan et al.	FutureFeed	Completed 2023	Peer-reviewed publication	Journal of Applied Phycology
The effects of processing on the in vitro antimethanogenic capacity and concentration of secondary metabolites of *Asparagopsis taxiformis*	Processing/Manufacture of Products	Vucko et al.	James Cook University	Completed 2017	Peer-reviewed publication	Journal of Applied Phycology
The mediterranean red alga *Asparagopsis*: A source of compounds against Leishmania	Product Development	Genovese et al.	University of Messina, Italy	Completed 2009	Peer-reviewed publication	Marine Drugs
Twice daily feeding of canola oil steeped with *Asparagopsis armata* reduced methane emissions of lactating dairy cows	Product Development	Alvarez-Hess et al.	James Cook University	Completed 2023	Peer-reviewed publication	Animal Feed Science and Technology
Using oil immersion to deliver a naturally-derived, stable bromoform product from the red seaweed *Asparagopsis taxiformis*	Processing/Manufacture of Products	Magnusson, et al.	University of Waikato and James Cook University	Completed 2020	Peer-reviewed publication	Algal Research

R&D Project Name	Supply Chain Element	Who	Association	Status	Document type	Output title
Benefits and risks of including the bromoform containing seaweed *Asparagopsis* in feed for the reduction of methane production from ruminants	Product Development	Glasson et al.	FutureFeed	Completed 2022	Peer-reviewed publication	Algal Research
Effect of the macroalgae *Asparagopsis taxiformis* on methane production and rumen microbiome assemblage	Product Development	Roque et al.	University of California	Completed 2019	Peer-reviewed publication	Animal Microbiome
Red seaweed (*Asparagopsis taxiformis*) supplementation reduces enteric methane by over 80 percent in beef steers	Product Development	Roque et al.	University of California	Completed 2021	Peer-reviewed publication	PLoS ONE
The red macroalgae *Asparagopsis taxiformis* is a potent natural antimethanogenic that reduces methane production during in vitro fermentation with rumen fluid	Product Development	Kinley et al.	FutureFeed	Completed 2016	Peer-reviewed publication	Animal Production Science
Changing the proportions of grass and grain in feed substrate impacts the efficacy of *Asparagopsis taxiformis* to inhibit methane production	Product Development	Kinley et al.	FutureFeed	Completed 2021	Peer-reviewed publication	American Journal of Plant Sciences
Inclusion of *Asparagopsis armata* in lactating dairy cows' diet reduces enteric methane emission by over 50 percent	Product Development	Roque et al.	University of California	Completed 2019	Peer-reviewed publication	Journal of Cleaner Production
Asparagopsis taxiformis decreases enteric methane production from sheep	Product Development	Li et al.	FutureFeed	Completed 2018	Peer-reviewed publication	Animal Production Science
Asparagopsis feedlot feeding trial	Product Development	Kinley	Meat and Livestock Australia	Completed 2018	Report	

R&D Project Name	Supply Chain Element	Who	Association	Status	Document type	Output title
In vitro response of rumen microbiota to the antimethanogenic red macroalga *Asparagopsis taxiformis*	Product Development	Machado et al.	James Cook University	Completed 2018	Peer-reviewed publication	Microbial Ecology
Antiviral activity of extract and purified compound from red macroalgae *Asparagopsis taxiformis* against H5N1 virus	Product Development	Shalaby and Shanab	Cairo University	Completed 2021	Peer-reviewed publication	Universal Journal of Pharmaceutical Research
Asparagopsis genus: What we really know about its biological activities and chemical composition	Product Development	Ponte et al.	University of Azores	Completed 2022	Peer-reviewed publication	Molecules
Asparagopsis taxiformis and *Asparagopsis armata* (Bonnemaisoniales, Rhodophyta): genetic and morphological identification of Mediterranean populations	Wild Population Assessment	Andreakis et al.	Stazione Zoologica, Italy	Completed 2004	Peer-reviewed publication	European Journal of Phycology
Assessing global range expansion in a cryptic species complex: insights from the red seaweed genus *Asparagopsis* (Florideophyceae)	Wild Population Assessment	Zanolla et al.	National University of Ireland	Completed 2018	Peer-reviewed publication	Journal of Phycology
Concise review of the genus *Asparagopsis* Montagne, 1840	Wild Population Assessment	Zanolla et al.	National University of Ireland	Completed 2022	Peer-reviewed publication	Journal of Applied Phycology
Endemic or introduced? Phylogeography of *Asparagopsis* (Florideophyceae) in Australia reveals multiple introductions and a new mitochondrial lineage	Wild Population Assessment	Andreakis et al.	James Cook University	Completed 2016	Peer-reviewed publication	Journal of Phycology
Modelling the distribution of the red macroalgae *Asparagopsis* to support sustainable aquaculture development	Wild Population Assessment	O'Mahony et al.	University College Cork, Ireland	Compelted 2021	Peer-reviewed publication	AgriEngineering

R&D Project Name	Supply Chain Element	Who	Association	Status	Document type	Output title
Molecular evidence for three separate cryptic introductions of the red seaweed *Asparagopsis* (Bonnemaisoniales, Rhodophyta) in South Africa	Wild Population Assessment	Bolton et al.	University of Cape Town and James Cook University	Completed 2011	Peer-reviewed publication	African Journal of Marine Science
Molecular phylogeny, phylogeography and population genetics of the red seaweed genus *Asparagopsis*	Wild Population Assessment	Andreakis	OPEN University of the UK	Completed 2006	Thesis	
Photosynthetic acclimation of different species and lineages of the invasive genus *Asparagopsis* to different temperatures	Wild Population Assessment	Zanolla et al.	National University of Ireland	Completed 2012	Conference paper	
Reproductive ecology of an invasive lineage 2 population of *Asparagopsis taxiformis* (Bonnemaisoniales, Rhodophyta) in the Alboran Sea (western Mediterranean Sea)	Wild Population Assessment	Zanolla et al.	National University of Ireland	Compelted 2017	Peer-reviewed publication	Botanica Marina
Sex and life-history stage alter herbivore responses to a chemically defended red alga	Wild Population Assessment	Verges et al.	Centre for advanced studies of Blanes, Spain	Completed 2008	Peer-reviewed publication	Ecology
Tetrasporangia in *Asparagopsis armata*	Wild Population Assessment	McLachlan	Atlantic Regional Laboratory, Canada	Completed 1967	Peer-reviewed publication	British Phycological Bulletin
The effects of the invasive seaweed *Asparagopsis armata* on native rock pool communities: Evidences from experimental exclusion	Wild Population Assessment	Silva et al.	Instituto Politécnico d e Leiria, Portugal	Completed 2021	Peer-reviewed publication	Ecological Indicators
The invasive *Asparagopsis taxiformis* hosts a low diverse and less trophic structured molluscan assemblage compared with the native *Ericaria brachycarpa*	Wild Population Assessment	Mancuso et al.	University of Palermo, Italy	Completed 2021	Peer-reviewed publication	Marine Environmental Research

R&D Project Name	Supply Chain Element	Who	Association	Status	Document type	Output title
The invasive genus *Asparagopsis* (Bonnemaisoniaceae, Rhodophyta): Molecular systematics, morphology, and ecophysiology of Falkenbergia isolates	Wild Population Assessment	NiChualain et al.	National University of Ireland	Completed 2004	Peer-reviewed publication	Journal of Phycology
The invasive seaweed *Asparagopsis taxiformis* erodes the habitat structure and biodiversity of native algal forests in the Mediterranean Sea	Wild Population Assessment	Mancuso et al.	University of Palermo, Italy	Completed 2022	Peer-reviewed publication	Marine Environmental Research
The more we search, the more we find: Discovery of a new lineage and a new species complex in the genus *Asparagopsis*	Wild Population Assessment	Dijoux et al.	The Research Institute for Development, New Caledonia	Completed 2014	Peer-reviewed publication	PLoS ONE
The red seaweed *Asparagopsis taxiformis* genome and integrative -omics analysis	Wild Population Assessment	Zhao et al.	University of Sunshine Coast	Completed 2022	Report	
Towards an integrative phylogeography of invasive marine seaweeds, based on multiple lines of evidence	Wild Population Assessment	Zanolla et al.	National University of Ireland	Completed 2016	Book Chapter	
Unusual bloom of tetrasporophytes of the non-indigenous red alga *Asparagopsis armata* in the northern Adriatic Sea	Wild Population Assessment	Orlando-Bonaca et al.	National Institute of Biology, Slovenia	Completed 2017	Peer-reviewed publication	Acta Adriatica
Developmental and reproductive strategies of two marine algae *Gracilaria corticata* (Gigartinales; Rhodophyta) and *Asparagopsis taxiformis* (Bonnemaisoniales; Rhodophyta) from Port Okha (Gujarat) west coast of India	Wild Population Assessment	Kumar et al.	University of Delhi	Completed 2000	Peer-reviewed publication	Indian Journal of Marine Sciences

R&D Project Name	Supply Chain Element	Who	Association	Status	Document type	Output title
Seasonality in Micronesian seaweed population and their biogeography as affecting wild crop potential	Wild Population Assessment	Tsuda	Univeristy of Guam	Completed 1982	Conference paper	Proceedings of republic of China: United States Cooperative Science Centre seminar on cultivation of economic algae
Cryptic diversity and phylogeographic patterns in the *Asparagopsis armata* species complex (Bonnemaisoniales, Rhodophyta) from New Zealand	Wild Population Assessment	Preuss et al.	Victoria University of Wellington	Completed 2022	Peer-reviewed publication	Phycologia
Defining culture requirements for reproduction and growth of *Asparagopsis taxiformis*, a Hawaiian native red alga	Wild Population Assessment	Mickelson	University of Hawaii	Completed 2013	Thesis	
There is more than meets the eye: Primary production of the invasive seaweed *Asparagopsis taxiformis* (Bonnemaisoniaceae, Rhodophyta) is provided by six cohorts with distinctive characteristics	Wild Population Assessment/Cultivation	Zanolla et al.	National University of Ireland	Completed 2018	Peer-reviewed publication	Aquatic Botany
Within-species and temperature-related variation in the growth and natural products of the red alga *Asparagopsis taxiformis*	Wild Population Assessment/Cultivation	Mata et al.	James Cook University	Completed 2016	Peer-reviewed publication	Journal of Applied Phycology
Systematics and life histories of New Zealand Bonnemaisoniaceae (Bonnemaisoniales, Rhodophyta): I. The genus *Asparagopsis*	Wild Population Assessment/Hatchery	Bonin and Hawkes	University of British Colombia	Completed 1987	Peer-reviewed publication	New Zealand Journal of Botany

R&D Project Name	Supply Chain Element	Who	Association	Status	Document type	Output title
Seaweed as a functional ingredient in the diet of farmed fish	Product Development	Thepot et al.	University of Sunshine Coast	Completed 2021	Thesis	
Seaweed dietary supplements enhance the innate immune response of the mottled rabbitfish, *Siganus fuscescens*	Product Development	Thepot et al.	University of Sunshine Coast	Completed 2021	Peer-reviewed publication	Fish and Shellfish Immunology
Effects of the macroalga *Asparagopsis taxiformis* and oregano leaves on methane emission, rumen fermentation, and lactational performance of dairy cows	Product Development	Stefenoni et al.	The Pennsylvania State University	Completed 2021	Peer-reviewed publication	Journal of Dairy Science
Effects of hydrogen peroxide on the content of major volatile halogenated compounds in the red alga *Asparagopsis taxiformis* (Bonnemaisoniaceae)	Cultivation	Mata et al.	James Cook University	Completed 2011	Peer-reviewed publication	Journal of Applied Phycology

Patent title	Supply chain element	Inventor	Organisation	Date	Status	Patent number
Asparagopsis life cycle improvements	Hatchery	Seaforest	Seaforest	5/12/2022	Filed	2022901266
Methods of cultivating *Asparagopsis*	Hatchery/Cultivation	Seaforest/University of Tasmania	Seaforest/University of Tasmania	5/12/2022	Filed	2022901265
Method of producing *Asparagopsis*	Hatchery/Cultivation	Seastock	Seastock	5/04/2023	Filed	2023901004
Animal feed additive and methods for its preparation	Product Development	Packer et al.	The Cawthron Institute Trust Board	25/11/2022	Approved	2022243984
Method of boosting innate immunity	Product Development	Paul, N.	University of the Sunshine Coast	25/06/2020	Approved	2020124167
Skin whitening and compacting plant essence cosmetic and preparation method thereof	Product Development	Guangming, P.		16/02/2022	Approved	107693406
Growth performance improvements in pasture and feedlot systems	Product Development	Tomkins et al.	JCU/MLA/CSIRO	22/02/2019	Approved	750371
A water soluble or water dispersible bolus article containing bromoform	Product Development	Tierney, D.	Bimeda Animal Health Limited	17/11/2022	Approved	2022237993
Anti-glycation whitening cream	Product Development	Wang He		13/08/2014	Approved	103976930
Laundry liquid for children, and preparation method thereof	Product Development	Zhang Qiming	Stokke Biotechnology	15/02/2017	Approved	106398883
Traditional Chinese medicine for treating allergic vasculitis	Product Development	Chen Yingdi		29/10/2014	Approved	104116870
Cosmetic as well as preparation method and application thereof	Product Development	Zhang Qiming	Stokke Biotechnology	9/08/2016	Approved	106176379
Child facial cream and preparation method thereof	Product Development	Zhang Qiming	Stokke Biotechnology	7/12/2016	Approved	106176466
Plant anti-oil anti-acne face cream	Product Development	Wang He		27/08/2014	Approved	104000769
Children's liquid soap and preparation method thereof	Product Development	Zhang Qiming	Stokke Biotechnology	11/01/2017	Approved	106309203
Skin Preparation for external use	Product Development	Ikeda Takahiko	Ikeda Corp	3/09/2009	Approved	2009196969

Patent title	Supply chain element	Inventor	Organisation	Date	Status	Patent number
Composition for removing dark circles and under-eye puffiness as well as preparation method and application thereof	Product Development	Cui Yingyun et al.	Guangzhou Keneng Cosmetic Research Co.	9/10/2020	Approved	111743833
Activator for fibroblast and skin preparation for external use containing the same	Product Development	Kamei Isamune et al.	Noevir Co Ltd	15/12/1998	Approved	1998330281
Skin external composition and functional food comprising *Asparagopsis taxiformis* extract	Product Development	Kim Han Young		26/08/2021	Approved	102293593
Method of increasing the productivity of a non-ruminant animal	Product Development	Paul, N.	University of the Sunshine Coast	24/06/2021	Approved	2021119729
Novel composition	Processing/Manufacture of Products	De Nys and Magnussun	James Cook University and Pacific Biotechnologies	6/12/2019	Approved	3890761
Hair conditioner for children and preparation method thereof	Product Development	Zhang Qiming	Stokke Biotechnology	30/08/2016	Approved	106176467
Skin-applying agent composition	Product Development	Koide Tomomasa	Lion Corp	22/02/2000	Approved	2000053528
Antibacterial and antiparasitic compound	Product Development	Reverter et al.	Univ de perpignan via domitia upvd	18/12/2020	Approved	3117734
Asparagopsis oil composition	Processing/Manufacture of Products	De Nys, R.	FutureFeed	6/12/2019	Approved	2594835
Traditional Chinese medicine formula for treating hyperthyroidism	Product Development	Zeng Lei	Qingdao Central Hospital	15/06/2016	Approved	105663825
Essence containing red alga extract and antarcticine and preparation method of essence	Product Development	Guo Zhijun	Houma economic development zone	17/05/2017	Approved	106667893
Promoter for producing collagen, and skin preparation for external use for preventing aging containing the same	Product Development	Kamei Isamune et al.	Noevir Co Ltd	30/05/1997	Approved	1998330280
Traditional Chinese medicinal composition for treating tumors	Product Development	Ren Lijie		25/02/2015	Approved	104367702

Patent title	Supply chain element	Inventor	Organisation	Date	Status	Patent number
Children's body wash and preparation method thereof	Product Development	Zhang Qiming	Stokke Biotechnology	11/01/2017	Approved	106309202
Acne removing essence microcapsule and preparation method thereof	Product Development	Jin Zhongén	Suzhou Cosmetic Materials Co Ltd	14/09/2018	Approved	108524295
Method for reducing total gas production and/or methane production in a ruminant animal	Product Development	Machado et al.	CSIRO/MLA/JCU	22/07/2016	Approved	722423
Children's shampoo and preparation method thereof	Product Development	Zhang Qiming	Stokke Biotechnology	11/01/2019	Approved	106265277
Bioreactor and method for culturing seaweed	Hatchery/Cultivation	Goldman et al.	Australis Aquaculture	2/09/2021	Approved	20210267150

24th International Seaweed Symposium Presentation title (2023) Hobart, Australia	Supply chain element	Presenter	Organisation
In silico-based multiomics approach to understanding *Asparagopsis*-organism interactions: implications for aquaculture	Wild Population Assessment	Tomas Lang	University of Sunshine Coast
A proteo-transcriptomic investigation of two life history stages for the red seaweed *Asparagopsis taxiformis*	Wild Population Assessment	Zubaida Parveen Patwary	University of Sunshine Coast
Unravelling the effects of microbiome manipulation in cultured *Asparagopsis taxiformis*	Cultivation	Silvia Blanco Gonzalez	University of Sunshine Coast
Asparagopsis expose: 50-odd years of unique science and marketing	Wild Population Assessment	Nick Paul	University of Sunshine Coast
The reproductive phenology of *Asparagopsis* in New Zealand - 35 years later	Wild Population Assessment	Alisa Mihaila	University of Waikato
Effects of light intensity on bromoform biosynthesis and gene expression in *Asparagopsis taxiformis*	Cultivation	Jessica Webb	University of Sunshine Coast
Effects of light quality and intensity on the growth and bromoform content of *Asparagopsis taxiformis*	Cultivation	Ana Campos	The Algarve Centre of Marine Sciences
Patterns of expression in the sea: Biophysical influences on halogenated natural products in *Asparagopsis*	Cultivation	Alexandra Campbell	University of Sunshine Coast
Research to inform *Asparagopsis armata* cultivation in Tasmania	Cultivation	Jeff Wright	University of Tasmania
Recovery and bioactivity of volatile halogenated natural products from post-harvest processing of *Asparagopsis taxiformis*	Processing/Manufacture of Products	David Heyne	University of Sunshine Coast

Appendix B – Survey questions for growers

Survey questions sent to Asparagopsis growers

1. **Company name**
2. **Nominated contact and details**
3. **Are you licensed by Future Feed to market/sell *Asparagopsis*?**
   Yes/No/currently seeking
4. **Have you got facilities/licenses/permits to grow *Asparagopsis*?**
   Land-based
   Marine Farm
   If yes to either land-based or marine farm, please state where your facility/farm is located and the size of the facility/farm (i.e. number of tanks, capacity and litres of water, area of lease)
5. **Are you currently collaborating with any universities, government agencies or external organistations?**
   Yes/No/currently seeking
6. **Do you currently hold any formal IP such as patents, reports, publications related to the *Asparagopsis* supply chain elements (Hatchery, Cultivation, Processing, Products)?**
   Yes/No/In review/currently seeking
7. **How advanced do you assess your company to be in the development of *Asparagopsis* phenology, lifecycle closure and hatchery techniques?**
   Start Up – we have progressed some cultivation using vegetative methods
   Early – we have researchers who know how to get spores to grow to tetrasporophyte stage
   Medium – we can get tetrasporophytes reproducing in laboratory conditions but have had limited success/not advanced to seeding to substrates.
   Expert – we are successfully cultivating *Asparagopsis* seaweed already. (If yes then please indicate quantity of harvest produced so far)
   Commercial – cultivating Asparagopsis from laboratory grown seedlings either in tanks or mariculture (If yes, please indicate quantity of harvest so far)
   Please indicate whether this applies to *A.armata*/*A. taxiformis*/Both

8. **So far, what have been the major challenges in developing cultivation and consistent supply?**
9. **Have you developed applied *Asparagopsis* lifecycle knowledge and hatchery techniques for *Asparagopsis* cultivation that you can share with others in the National Hatchery Network?**
   Yes – happy to openly share the knowledge we have with others in the industry
   Yes – but would need an NDA or other agreement in place so that the information is not shared outside of the National Hatchery Network
   Yes – but would need to agree conditions with the National Hatchery Network such as preferential deal for access to seedstock or license fee (only if IP protections are in place)
   No – not willing to share any knowledge we have developed on the lifecycle and hatchery techniques for *Asparagopsis* cultivation.
10. **Where do you see the major knowledge gaps moving forward?**

11. **What do you foresee as potential future obstacles to establishing a National Hatchery Network?**
12. **Where would you like to see research focussed in the future? Please list in order of priority.**
13. **Do you see a commercial benefit in being able to get access to clean, quality, genetically appropriate seedstock/seeded ropes?**
    - Yes - I just want to buy seedstock cultures or seeded ropes/substrates from a supplier
    - Yes – perhaps initially but we have plans to develop our own hatchery so would benefit more from support to develop our own seedstock
    - No – we are totally self sufficient for seedstock but could benefit from support and collaboration for optimisation of our hatchery
    - No – we don't need help and are intending to sell seeded rope/seedstock commercially
14. **Would you contribute to a biological database (e.g. genetics, growth habits, tolerances, bromoform content)?**
15. **Do you think a selective breeding program has a role in the development of the *Asparagopsis* industry, and how far away do you think that is?**
16. **What do you see as priority activities for the National Hatchery Network?**

Thank you for your time. We would like to discuss your answers and the National Hatchery Network in more detail with your nominated contact. Please provide an email and choose a time that suits you.

Appendix C – Survey questions for state governments

Survey questions sent to State Government Fisheries Departments through the AFMF – Seaweed Working Group

1. **State government department name**
2. **Nominated contact and details**
3. **Do you have facilities that could be used for Asparagopsis research?**
   Land-based
   Marine Farm
   If yes to either land-based or marine farm, please state where your facility/farm is located and the size of the facility/farm (i.e. number of tanks, capacity and litres of water, area of lease)
4. **Are you currently undertaking any Asparagopsis research, either internally or through external collaborations?**
   Yes, internal
   Yes, collaboration
   No
   Please provide details
5. **Are you aware of any government funded projects researching Asapragopsis in you state?**
   Yes/No/If yes, please provide details
6. **Do you currently hold any formal IP such as patents, reports, publications related to the *Asparagopsis* supply chain elements (Hatchery, Cultivation, Processing, Products)?**
   Yes/No/In review/currently seeking
7. **How many licenced Asparagopsis growers are you aware of in your state? If you are happy to share details, please do.**
8. **What area of marine estate is allocated for Asparagopsis cultivation?**
9. **Do you have a policy in place to guide the development of Asparagopsis aquaculture?**
   Yes/No/Under review/Please provide details
10. **Would your department consider providing State government funding towards an industry led hatchery scheme to support a satellite hatchery for Asparagopsis research in your state?**
    Yes/No/Uncertain at this time/Please provide details
11. **Is there any budget allocation for seaweed aquaculture research and development in your State?**
    Yes/No/Uncertain/Please provide details
12. **So far, what do you believe to be the major challenges in developing cultivation and consistent supply?**
13. **Where do you see the major knowledge gaps or risks that require more R&D?**
14. **What do you foresee as potential future obstacles to establishing a National Hatchery Network?**
15. **Where would you like to see Asparagopsis cultivation research focussed in the future? Please list in order of priority.**

16. **What do you see as priority activities for the National Hatchery Network?**

Thank you for your time. We would like to discuss your answers and the National Hatchery Network in more detail with your nominated contact. Please provide an email and choose a time that suits you.