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Foreword

The Australian seaweed industry has a vision to be a $1.5 billion industry by 2040, driven by increasing demand for sustainable food, bioactive compounds and innovative environmental applications. Australia's vast and diverse marine environment holds immense potential for the cultivation of native seaweed species and the development of the industry.

Despite its infancy, the industry is poised to contribute significantly to both economic growth and environmental sustainability. However, expansion of seaweed aquaculture must be underpinned by robust biosecurity measures to ensure productivity, marketability and ecological integrity.

This project addresses a critical gap in the development of the industry, namely biosecurity planning. Globally, the intensification of seaweed aquaculture has been accompanied by an increase in pest and disease outbreaks, threatening crop viability and market access. Without strategic biosecurity measures, Australia's fledgling industry risks similar vulnerabilities. Also, unmanaged biosecurity threats could negatively impact wild populations and marine ecosystems, undermining both environmental sustainability and public support for aquaculture activities.

The findings of this research highlight both the opportunities and challenges facing the Australian seaweed industry. Key discoveries include a recognition of knowledge gaps regarding specific pests and diseases of Australian seaweeds, alongside evidence from global practices demonstrating the effectiveness of generic biosecurity measures. The project's outcomes emphasise the need for proactive management strategies to mitigate risks such as disease outbreaks, pest invasion, and genetic dilution. The report provides practical guidelines and a biosecurity action plan tailored to the unique characteristics and challenges of Australian seaweed aquaculture.

Producers and industry stakeholders are urged to integrate these biosecurity measures as a standard component of their operations. Doing so will not only protect individual enterprises but also ensure the collective resilience of the industry. By fostering a proactive biosecurity culture, the Australian seaweed sector can realise its potential as a sustainable and competitive player in the global market.

This work has been made possible through the dedication of researchers, industry representatives, and government stakeholders. Their collaborative efforts have laid the foundation for a thriving and resilient seaweed industry in Australia, one that balances economic opportunity with environmental stewardship.

This project was completed as part of the AgriFutures Emerging Industries Program, which aims to help emerging industries in Australia grow and reach new markets. For more information and resources, visit agrifutures.com.au/emerging-industries.

Dr Olivia Reynolds
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- Adam Main and Jay Dent – CH4 Global
- Shannen Smith – South Australian Research and Development Institute Aquatic and Livestock Sciences (Marine Ecosystems)
- Karina Worral and Melinda Coleman* – New South Wales Department of Primary Industries
- Warren Atkins – Sea Health Products
- Jo Lane, Thanh Hoang, Margie Rule* and Allyson Nardelli – Australian Sustainable Seaweed Alliance
- George Wood and Jill Carr – Flinders University
- Ananda Santos and Almendra Rodriguez Dominguez* – CleanEyre Global
- Brett Herbert* – Northern Territory Department of Industry, Tourism and Trade (Fisheries Division)
- Cynthia Iha* – CSIRO Algal Culture Collection
- Jo Klemke* – Victorian Fisheries Authority
- Jodie O'Malley* and Samantha Bridgwood* – Western Australian Department of Primary Industries and Regional Development
- Camille White* – Institute of Marine and Antarctic Studies, University of Tasmania
- Dianne Maynard* and Mei Ooi* – Tasmanian Department of Natural Resources and Environment
- Stephanie Grimmett* – Queensland Department of Agriculture and Fisheries
- Pia Winberg* – Venus Shell Systems
- Steven Clarke* – Fisheries Research and Development Corporation seaweed project facilitator

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SARDI respects Aboriginal people as the state's first people and nations. We recognise Aboriginal people as traditional owners and occupants of South Australian land and waters. We pay our respects to Aboriginal cultures and to Elders past, present and emerging.

AgriFutures Australia acknowledges the First Nations people of Australia as the traditional custodians of the lands and waters on which we live, learn and work. We pay our respects to past, present and future Elders of these nations. In particular, we acknowledge the Wiradjuri people of Australia, the traditional custodians of the lands and waters where AgriFutures' head office is located.

Contents

Executive summary

This report details seaweed pests, diseases, environmental biosecurity issues and management strategies for addressing biosecurity risks relevant to the emerging Australian seaweed industry.

Biosecurity planning guidelines and a biosecurity action plan for the seaweed industry have been developed based on the information presented in this report and in consultation with stakeholders. The guidelines will facilitate seaweed industry enterprises to develop operation-specific biosecurity plans, supporting action plan goals of industry productivity and sustainability while minimising risks to seaweed health and the environment.

Background

Increasing demand for seaweeds and seaweed products, coupled with recognition of the potential for Australian seaweeds to yield novel valuable bioproducts, is driving interest in the development of an Australian seaweed industry. Wild harvest, primarily of beach-cast material, of Australian seaweeds currently occurs at a small scale, but significant industry expansion will rely on seaweed aquaculture. Seaweed cultivation in Australia is also of interest for conservation and restoration purposes.

Pests and diseases cause significant problems for aquaculture generally, including for seaweed cultivation globally. Pests and diseases can negatively affect seaweed aquaculture through impacts on seaweed health, productivity and product quality. Seaweed aquaculture also poses environmental biosecurity risks through spreading pests or diseases to wild stocks or through genetic impacts, particularly genetic dilution and hybridisation, due to inter-breeding of seaweeds from different areas. To ensure the productivity and sustainability of the emerging Australian seaweed industry, it is important that these biosecurity risks are managed.

The specific aims of this project were to:

1. Obtain information on seaweed pests and diseases, and environmental biosecurity threats associated with seaweed aquaculture.
2. Identify management strategies that can mitigate seaweed industry biosecurity risks.
3. Collate information and develop a seaweed industry biosecurity action plan and guidelines in consultation with relevant stakeholders.

Methodology

Researchers from the South Australian Research and Development Institute (SARDI) reviewed literature and facilitated a workshop with Australian seaweed industry stakeholders to develop knowledge on seaweed pests and diseases, and environmental biosecurity issues relevant to Australian species. The workshop included representatives from aquaculture enterprises and jurisdictional aquatic health and aquaculture managers, and relevant researchers in plant and seaweed health and genetics. Biosecurity guidelines for the industry were developed using knowledge obtained from the literature review and workshop, approaches applied for other aquatic organisms, and in consultation with relevant stakeholders.

Key findings

The literature review and workshop determined that knowledge on specific pests and diseases of Australian seaweeds is lacking. Important pests and pathogens are, however, likely to occur in Australian seaweeds, including disease-causing water moulds, bacteria, fungi and viruses. Seaweeds host many epiphytic organisms that can include pests of seaweeds and invasive aquatic species. Invasive species may also be spread by equipment and media (water and substrates) used for transport and cultivation.

Many seaweed diseases are environmentally mediated and are due to opportunistic pathogens that are commonly present but only cause disease where other stressors occur. These pathogens may be impractical to exclude from cultivation systems, with good husbandry important in prevention, but basic biosecurity measures will still be effective at reducing the spread and impacts of these diseases. Other pests and pathogens should be excluded from cultivation systems as far as practical. Although the specific pests and diseases relevant to Australia seaweeds are yet to be identified, several generic management approaches have been shown to be effective at preventing the spread of seaweed pests and disease.

Information on management approaches has been collated suitable to address risks posed by important pathways (including water, stock movements, vessels, and equipment) relevant to the several different cultivation systems that may be applied for seaweed aquaculture. Information on biosecurity hazards and management strategies was used to develop biosecurity guidelines for the seaweed industry.

The biosecurity guidelines have been developed to be flexible to adapt to changing needs as the industry develops and knowledge increases.

Implications

The information provided in this report and biosecurity guidelines developed by this project will support the seaweed industry biosecurity action plan goal and help to guide biosecurity planning for the Australian seaweed industry. Biosecurity plans will assist the emerging industry to maintain health and productivity in cultivated seaweeds, facilitate market access, fulfil regulatory requirements, and achieve environmental sustainability.

A lack of knowledge on the specific pests and diseases affecting or carried by Australian cultivated seaweeds, however, means that precautionary approaches will be needed, at least initially.

Recommendations

Seaweed industry enterprises will need to develop and implement biosecurity plans specific to their operations, noting that flexible and precautionary approaches will likely be needed. Collating and sharing information across industry and government on pest and disease issues as these arise will assist in refining biosecurity knowledge and practices for the Australian seaweed industry. The guidelines developed focus currently on generic approaches, which are valuable for all aquaculture industries to protect against unforeseen biosecurity threats, but where specific pest or disease issues occur, diagnostic methods and tailored management strategies should be developed and incorporated into future industry biosecurity planning.

Keywords: Seaweeds, aquaculture, biosecurity, pests, pathogens, invasive aquatic species

Introduction

Seaweed farming is not an established industry in Australia, but is of interest to meet increasing demand for seaweed products, of which Australia is a net importer (Lee 2010; Roos *et al*. 2018; Kelly 2020).

Seaweeds are widely used as food in Asia, and with globalisation and growing recognition of the sustainability and health benefits of eating seaweeds, seaweeds are increasingly used as, or incorporated in, food in many parts of the world (McHugh 2003; White and Wilson 2015; Buschmann *et al*. 2017; Skrzypczyk *et al*. 2018). Aquaculture production of edible seaweeds is therefore increasing rapidly to meet these demands (Buschmann *et al*. 2017). Several native Australian species, including the golden kelp,[1] *Ecklonia radiata*, are palatable and nutritious (Chopin *et al*. 2001; Charoensiddhi *et al*. 2015; Charoensiddhi *et al*. 2017; Skrzypczyk *et al*. 2018), and of interest as food or an ingredient in functional foods.

Seaweed extracts, including hydrocolloids and bioactive compounds, are also in growing demand (Smit 2004; Holdt and Kraan 2011; Thomas and Kim 2011; Lorbeer *et al*. 2013; White and Wilson 2015). Seaweed hydrocolloids are used as gelling agents in many food products and in a range of industrial and biomedical applications (McHugh 2003; Bixler and Porse 2011; Holdt and Kraan 2011; White and Wilson 2015; Buschmann *et al*. 2017). These hydrocolloids include agar, produced by red seaweeds of the orders Gracilariales and Gelidiales; carrageenan, produced by the red seaweed order Gigartinales; and alginates, which are commercially sourced from the brown seaweed orders Laminariales and Fucales (Bixler and Porse 2011; White and Wilson 2015).

Many seaweeds produce bioactive compounds, including anti-ageing, anti-tumour, anti-viral, anti-bacterial and anti-fungal activities, that are used in functional foods, cosmetics, medicines, and pesticides (Smit 2004; Gupta and Abu-Ghannam 2011; Holdt and Kraan 2011; Thomas and Kim 2011; Lorbeer *et al*. 2013; Buschmann *et al*. 2017). Several seaweeds, in particular *Asparagopsis* spp. (order Bonnemaisoniales), show potential for mitigating methane production by cattle when included in livestock feed (Machado *et al*. 2018; Kelly 2020), and cultivation of *Asparagopsis* spp. is therefore of increasing interest for this application. Two species of *Asparagopsis* are native to Australia, and are of particular focus for the development of an Australian seaweed industry. Australia's diverse seaweed flora, however, has the potential to yield novel bioactive compounds, and be utilised as food or as a source of hydrocolloids (Kirkendale *et al*. 2010; Lee 2010; Winberg *et al*. 2011; Lorbeer *et al*. 2013; Roos *et al*. 2018).

Despite increasing interest in developing the Australian seaweed industry, several barriers to industry development exist (Kelly 2020). Biosecurity is recognised as critical for industry development globally (Cottier-Cook *et al*. 2016) and has been identified as an important area of concern for the emerging seaweed industry in Australia (Kelly 2020). The intensification of seaweed aquaculture globally has led to increasing pest and disease outbreaks in farmed seaweed in many countries (Ward *et al*. 2019). Pest and disease outbreaks in aquaculture result in production losses through mortalities of farmed biomass and reduced crop quality (Palić *et al*. 2015; Ward *et al*. 2019; Murua *et al*. 2023). Pests and diseases can also cause problems for industry by reducing market access and social acceptance of aquaculture activities (Palić *et al*. 2015; Spillias *et al*. 2022; Murua *et al*. 2023). Aquaculture also poses environmental biosecurity risks through the potential introduction or spread of pests, diseases, and invasive species to native populations (Campbell *et al*. 2019b; Bhuyan 2023;

[1] Standard aquatic plant names are used throughout this document for taxa where standard names have been assigned that differ from the scientific (genus) name. Other taxa are referred to using current scientific names following the World Register of Marine Species (WoRMS). Scientific names, following WoRMS, are also used when referring to specific taxa within groups that share the same standard name.

Murua *et al*. 2023). The establishment of seaweed pests and diseases in wild stocks can create a reservoir for reinfection of cultivated crops in addition to impacts on wild populations (Palić *et al*. 2015; Valero *et al*. 2017), while invasive aquatic species can have far-reaching environmental and economic impacts (Schaffelke and Hewitt 2007; Williams and Smith 2007; Petrocelli and Cecere 2015). Effective biosecurity minimises risks of production loss due to pests and diseases and is important to maintain product quality and market access, and to protect wild populations and the environment (Palić *et al*. 2015).

Within this context, AgriFutures Australia engaged the South Australian Research and Development Institute (SARDI) to develop biosecurity planning guidelines for the Australian seaweed industry. The Australian Government's Department of Agriculture, Fisheries and Forestry (DAFF) has published generic national guidelines for aquaculture biosecurity planning (SCAAH 2016). Although these generic guidelines were developed primarily considering fish and invertebrate cultivation and focus on aquatic animal disease management, the framework and general principles are applicable to all forms of aquaculture, and following the same framework ensures consistency in biosecurity planning across aquaculture industries. The generic guidelines were therefore used as a basis for the development of biosecurity planning guidelines for the seaweed industry.

To be effective, biosecurity management needs to be practical and cost effective while addressing key risks and fulfilling regulatory requirements (Palić *et al*. 2015; SCAAH 2016; Cottier-Cook *et al*. 2022). To facilitate biosecurity planning for an aquaculture industry, SCAAH (2016) recommends documenting existing biosecurity practices that have been demonstrated to be effective, and consulting with stakeholders to identify and prioritise biosecurity threats and potential management strategies. The general process for developing biosecurity plans at an industry and enterprise level then involves identifying hazards relevant to the operation, carrying out risk assessment to prioritise hazards for management, and developing appropriate strategies to manage risks.

Because the seaweed industry is not yet well-developed in Australia, this project reviewed global knowledge on seaweed pests, diseases and biosecurity issues, and on management strategies applied to seaweed aquaculture in countries with established seaweed industries. Relevant biosecurity management strategies used in Australian fish and invertebrate aquaculture industries were also reviewed. Biosecurity guidelines were developed in consultation with industry and government stakeholders, and relevant researchers, using knowledge obtained from the literature review and stakeholder consultation.

This report includes information compiled from the literature review and stakeholder consultation that was used to develop the seaweed industry biosecurity guidelines. The guidelines, incorporating stakeholder feedback, are included as an appendix to this report.

Methods

A literature review was carried out to obtain information on seaweed pests, diseases and environmental biosecurity risks associated with seaweed aquaculture, and to investigate potential management actions to address biosecurity risks.

To obtain relevant literature, searches were performed using Scopus, Web of Science and Google Scholar. A non-exhaustive list of terms included in searches is shown in Table 1. Searches included one or more terms for seaweed, plus one or more other terms targeting results for diseases, pests, environmental biosecurity, or relevant strategies to mitigate or address risks. Books, peer-reviewed articles, scientific and technical reports, and web pages were considered.

Table 1. Search terms applied for the literature review.

Category	Search terms used
Seaweed	seaweed, macroalga, kelp, Laminariales, Fucales, Gigartinales, Bonnemaisoniales, Bangiales, *Ecklonia*, *Asparagopsis*, plus other species and taxon names
Disease	disease, pathogen, parasite, bacteria, virus, protist, fungi, oomycete, water mould, plus specific disease names
Pests/parasites	pest, parasite, epiphyte, endophyte, fouling, grazer, invasive
Environmental biosecurity	biosecurity, environmental impact
Actions/strategies	treatment, mitigation, management

Abstracts or summaries of potentially relevant literature from the search results were reviewed and the full text obtained for all publications regarded as relevant. Where publications cited relevant literature not returned in initial searches, those cited publications were also obtained and reviewed. Information was collated, giving precedence to peer-reviewed and more recent literature where conflicting information was found, or where updates had occurred, e.g., to taxonomy or recognised pathogens associated with a disease.

Information on the dynamics of pest disease spread to inform the definition of health management units was obtained for pests and diseases of marine animals because data specific to seaweeds were sparse. Literature searches for this aspect were guided by information on the types of diseases likely to be present in seaweed from the initial literature review. Search terms used were a combination of terms for relevant pathogen types (e.g., virus, bacteria, oomycete), and terms for transmission or spread in the marine environment (e.g., waterborne transmission or infection).

The Fisheries Research and Development Corporation (FRDC)-funded project *Developing biomass assessment approaches, harvest methodologies and biosecurity knowledge for wild-harvest of seaweeds in southern Australia* (FRDC 2021-112) commenced in April 2023. The biosecurity component of the FRDC project included a review of biosecurity risks associated with seaweed harvest and translocation, particular for seaweeds of commercial interest in southern Australia, and the development of a framework to define health management units for seaweeds and to assess translocations (Wiltshire *et al.* in prep.). Information on seaweed pest and disease threats, environmental biosecurity concerns, and management strategies was shared between this project and FRDC 2021-112 to avoid duplication of effort and ensure all relevant information is made available to all stakeholders. Relevant information obtained as part of FRDC 2021-112 was made available and incorporated in the review for this report. This report builds on initial knowledge obtained as part of FRDC 2021-112 by considering additional seaweeds of potential commercial interest and all seaweed industry activities and potential biosecurity concerns.

A full-day workshop including seaweed industry representatives, government aquaculture and aquatic health managers, and seaweed researchers was held at SARDI Aquatic Sciences, West Beach, Adelaide on 13 December 2023. The workshop used a hybrid format; 17 people attended in-person while 15 attended online. Industry stakeholders who attended the meeting included representatives from the Australian Sustainable Seaweed Alliance (ASSA), CH4 Global, CleanEyre Global, Sea Health Products and Venus Shell Systems. Jurisdictional representatives were present from Primary Industries and Regions South Australia (PIRSA), New South Wales Department of Primary Industries (NSW DPI), Victorian Fisheries Authority (VFA), Western Australian Department of Primary Industries and Regional Development (WA DPIRD), Northern Territory Department of Industry, Tourism and Trade (NT DITT), Tasmanian Department of Natural Resources and Environment (NRE Tas), and Queensland Department of Agriculture and Fisheries (QDAF). Also present were researchers from Western Australia, South Australia, New South Wales, Victoria and Tasmania with expertise in seaweed and/or plant health, seaweed reproduction, cultivation for aquaculture or restoration, and genetic structure of Australian seaweeds.

The workshop was facilitated by the project team, comprising:

- Kathryn Wiltshire, Marty Deveney and Jason Tanner – SARDI Aquatic and Livestock Sciences (Marine Ecosystems)
- Nicole Thompson – SARDI Crop Sciences (Molecular Diagnostics)
- Sasi Nayar – SARDI Aquatic and Livestock Sciences (Aquaculture)
- Matthew Bansemer – PIRSA (Fisheries and Aquaculture)

Workshop participants (*online) in addition to the project team were:

- Adam Main and Jay Dent – CH4 Global
- Shannen Smith – SARDI Aquatic and Livestock Sciences (Marine Ecosystems)
- Karina Worral and Melinda Coleman* – NSW DPI
- Warren Atkins – Sea Health Products
- Jo Lane, Thanh Hoang, Margie Rule*, and Allyson Nardelli – ASSA
- George Wood and Jill Carr – Flinders University
- Ananda Santos and Almendra Rodriguez Dominguez* – CleanEyre Global
- Brett Herbert* – NT DITT (Fisheries Division)
- Cynthia Iha* – CSIRO Algal Culture Collection
- Jo Klemke* – VFA
- Jodie O'Malley* and Samantha Bridgwood* – WA DPIRD
- Camille White* – Institute of Marine and Antarctic Studies, University of Tasmania
- Dianne Maynard* and Mei Ooi* – NRE Tas
- Stephanie Grimmett* – QDAF
- Pia Winberg* – Venus Shell Systems
- Steven Clarke* – Fisheries Research and Development Corporation seaweed project facilitator

At the workshop, the project team presented information on:

- The process of biosecurity planning and its importance for aquaculture industries.
- Information on key pest and disease threats to seaweed aquaculture globally.
- Information on assessing risks and determining appropriate mitigation measures.
- An outline of the emergency response process, with examples for plant pests and diseases.
- Information on biosecurity plan implementation, review and auditing.

The workshop included facilitated discussions with attendees on:

- Likely cultivated species, types of cultivation systems and areas for cultivation.
- Key pathways for pest and disease introduction.
- Prioritising key biosecurity threats for seaweed aquaculture.
- Contingency planning and emergency preparedness for seaweed aquaculture.
- Potential biosecurity measures for seaweed cultivation in different cultivation systems,[2] including:
    - Closed systems – e.g., recirculating aquaculture systems
    - Semi-closed systems – e.g., flow-through tanks and ponds
    - Semi-open and open systems – at-sea grow-out using infrastructure that provides some control over stock, such as longlines, and out-planting for restoration or replenishment of wild stocks.

Following the workshop, further consultation was undertaken involving Steven Clarke (FRDC) and Jens Knauer (ASSA). Information from the literature review, workshop and additional consultation was used to develop draft biosecurity planning guidelines for the seaweed industry. The guidelines were developed following the national guidelines for developing generic aquaculture biosecurity plans (SCAAH 2016) and with reference to biosecurity plans developed for other aquaculture sectors (DAFF 2023).

Draft guidelines were circulated to industry and government stakeholders to review. Comments were received from Stephanie Grimmett, Ananda Santos, Samantha Bridgwood and Jay Dent. The guidelines were revised based on the stakeholder feedback and the revised guidelines are included as an appendix to this report.

[2] Cultivation system definitions used herein are consistent with those used in the national guidelines for developing generic aquaculture biosecurity plans (SCAAH 2016).

Review of global seaweed industry biosecurity risks and practices

Biosecurity risks in aquaculture fall into two main categories: risks to the crop being cultivated and risks to the environment. These categories are not mutually exclusive, and some risks overlap.

Key risks to the cultivated crop are outbreaks of diseases, parasites and pests that cause mortality, reduce production or impair crop quality and value (Ward *et al*. 2019; Kambey *et al*. 2021c; Behera *et al*. 2022a; Murua *et al*. 2023). Environmental biosecurity risks include the potential for diseases and pests to be spread or introduced to wild stocks, for invasive species to be introduced, or for gene flow from cultivated crops to negatively impact genetic diversity of wild populations (Naylor *et al*. 2001; Campbell *et al*. 2019b; Barbier *et al*. 2020; Bhuyan 2023; Murua *et al*. 2023).

Seaweed diseases

Several diseases of seaweeds, both wild and cultivated, have been described, although few causative agents are well characterised (Ward *et al*. 2019; Strittmatter *et al*. 2022). Organisms associated with seaweed disease include bacteria, fungi, water moulds (oomycetes), single-celled eukaryotes (including amoebae), and endophytic algae. Pathogenicity of the organisms associated with disease has not been demonstrated in all cases, while in other cases, organisms have been demonstrated to induce disease only under specific conditions, e.g., suboptimal environmental conditions or where physical damage is present, such as from grazing (Campbell 2011; Hudson and Egan 2022; Li *et al*. 2022; Murua *et al*. 2023).

Common signs of seaweed diseases include colour changes, particularly bleaching, thallus decay, often beginning with small holes, and abnormal growths such as galls or deformation. Bleaching in seaweeds reflects a loss of photosynthetic pigments, which likely leads to poorer photosynthetic performance and reduced growth (Campbell 2011; Beattie *et al*. 2018; Wang *et al*. 2021). Bleaching is often also accompanied by, or progresses to, necrosis. Decay and necrosis involve loss of seaweed tissue, with the loss of whole plants possible where tissue degrades at or near to the culture substrate (e.g., ropes or net), or where plant mortality results. Thallus deformations may also lead to losses of plants from culture ropes due to increased drag or reduced attachment strength (Neill *et al*. 2008; Murúa *et al*. 2019).

Disease often results in lower product quality and value. Lower value can occur due to undesirable appearance because of damage, colour change or abnormal growth, or due to changes in biochemical composition or reduced yield of product, e.g., agar, carrageenan or alginate (Bernard 2018; Wang *et al*. 2021; Ward *et al*. 2021; Hudson and Egan 2022). Diseases affecting the nursery stages can considerably impact seedling supply (Ling *et al*. 2022).

Key seaweed pests and diseases are summarised in Table 2 and detailed below. Table 2 is organised by seaweed taxonomic group to allow stakeholders with an interest in seaweed cultivation to identify key pests and diseases for a particular taxon of interest. It should be noted, however, that many types of seaweed disease occur across multiple taxonomic groups, as discussed below.

Table 2. Reported diseases, parasites and pests of seaweeds. References provided are key sources for information presented in this table but are not a comprehensive reference list for each issue. Additional citations and details are provided in the text.

Taxon/taxa affected	Disease/issue common name	Disease symptoms/impacts	Pest or pathogen(s) involved	Key references
Gigartinales: Solieriaceae (Jellyweeds)				
Kappaphycus and *Eucheuma* spp.	Ice-ice disease (IID)	Bleaching, thallus softening and decay, detachment of thalli from cultivation lines	Bacteria from *Cytophaga-Flavobacterium* and *Vibrio-Aeromonas* complexes, Ascomycetes *Aspergillus* spp. and *Phoma* spp.	Tahiluddin and Terzi (2021); Behera *et al*. (2022a); Bernard (2018); Ward *et al*. (2019); Faisan *et al*. (2021); Sugumaran *et al*. (2022)
Kappaphycus and *Eucheuma* spp.	Epiphytic filamentous algae (EFA), goosebumps	Black spots, thallus deformity, filamentous algae penetrating the thallus, compromised product quality, potential secondary infection and grazing of damaged thallus	Red seaweed *Melanothamnus apiculata*	Ward *et al*. (2019); Faisan *et al*. (2021); Behera *et al*. (2022a); Sugumaran *et al*. (2022); Murua *et al*. (2023)
Kappaphycus and *Eucheuma* spp.	Macro-epiphytes	Seaweeds entangled with or loosely attached to thalli, growth of crop compromised due to competition	Seaweed *Gracilaria* sp., *Hypnea* sp., *Laurencia* sp. *Cladophora* sp., *Ulva* sp., *Sargassum* spp.	Ward *et al*. (2019); Largo *et al*. (2020a); Faisan *et al*. (2021); Sugumaran *et al*. (2022)
Kappaphycus and *Eucheuma* spp.	Grazing	Loss of biomass, potential secondary infection	Herbivorous fish, amphipods	Bernard (2018), Faisan *et al*. (2021); Sugumaran *et al*. (2022)
Gigartinales: Gigartinacae				
Chondrus crispus (Irish moss)	Unnamed	Apical bleaching and damage leading to erosion, secondary infections, mortality	Oomycete *Petersenia pollagaster*	Craigie and Correa (1996); Craigie *et al*. (2019); Behera *et al*. (2022a)
Chondrus crispus	Green spot or green rotting	Frond holes, blade decay, cessation of growth	*Cytophaga/Flavobacterium* like bacteria	Craigie and Correa (1996); Behera *et al*. (2022a), Hudson and Egan (2022)
Chondrus crispus	Galls	Gall formation	Bacteria – isolated but not identified	Bernard (2018)
Chondrus crispus and *C. ocellatus*	Epiphytes	Reduced growth and product quality	Seaweed *Ectocarpus*, *Mikrosyphar*, *Ulva* spp.	Ogandaga *et al*. (2017); Craigie *et al*. (2019)
Chondrus crispus and *C. ocellatus*	Filamentous green endophyte	Lesions, frond holes, secondary infection, reduced reproductive output	Green algae *Ulvella* spp.	Choi *et al*. (2015); Craigie *et al*. (2019)
Iridaea laminarioides	Deformative gall disease	Galls	Cyanobacteria *Pleurocapsa*	Egan *et al*. (2014)
Gracilariales: Gracilariaceae				
Gracilariaceae	Epiphytes	Reduced growth and product quality	Many seaweeds, diatoms	Aroca *et al*. (2020)
Agarophyton chilensis	Green filamentous algae	Overgrowth and smothering of crops, large biomass losses	*Rhizoclonium*-like sp.	Aroca *et al*. (2020)
Agarophyton vermiculophyllum	Tip bleaching	not detailed	Bacteria *Kordia algicida*	Saha *et al*. (2019); Hudson and Egan (2022)
Gracilariopsis heteroclada, *Gracilaria verrucosa*	Rotten thallus syndrome	Thallus decay	Bacteria *Bacillus* spp. and *Vibrio* spp.	Egan *et al*. (2014); Martinez and Padilla (2016); Martinez and Padilla (2017); Ward *et al*. (2019)
Gracilaria spp	Ice-Ice disease	Bleaching, thallus decay	Bacteria *Flavobacterium*, amoebae	Bernard (2018); Hudson and Egan (2022), Zainuddin *et al*. (2019)

Taxon/taxa affected	Disease/issue common name	Disease symptoms/impacts	Pest or pathogen(s) involved	Key references
Gracilaria spp	Biofouling	Reduced production, increased risk of breakage and dislodgment	Bivalves *Gaimardia bahamondei*, *Choromytilus chorus*, and *Semimytilus algosus*; green algae *Ulva* spp.	Behera *et al*. (2022a); Chowdhury *et al*. (2022)
Gracilaria conferta	Apical necrosis	Apical decay	Bacteria *Flavobacterium-Cytophaga* group bacteria	Hudson and Egan (2022)
Gracilaria conferta	White-tip/brown points disease	Not detailed	Bacteria – isolated but not identified	Egan *et al*. (2014)
Gracilaria gracilis	Decay	Cell wall degradation	Bacteria *Pseudoalteromonas gracilis*	Zainuddin *et al*. (2019)
Gracilariopsis lemaneformis	Bleached disease	Bleaching	Bacteria *Aquimarina latercula*, *Agarivorans albus*, *Brachybacterium* sp.	Hudson and Egan (2022), Liu *et al*. (2019)
Gracilariopsis lemaneformis	White-tip disease	Not detailed	Bacteria *Thalassospira* sp., *Vibrio parahaemolyticus*	Egan *et al*. (2014)
Bonnemaisoniales: Bonnemaisoniaceae				
Delisea pulchra	Bleaching disease	Localised pigment loss, reduced growth, photosynthetic performance and fecundity, increased susceptibility to grazers	Bacteria *Aquimarina* sp., *Agarivorans*, *Alteromonas*, *Nautella italica*, *Phaeobacter*	Campbell *et al*. (2014); Egan *et al*. (2014); (2016); Hudson and Egan (2022)
Asparagopsis spp.	Oomycetes	Not detailed	*Olpidiopsis* spp.	Li *et al*. (2010); Badis *et al*. (2018); Badis *et al*. (2019)
Ceramiales (*Heterosiphonia*, *Bostryichia*)	Oomycetes	Colour changes, lesions, thallus decay, abnormal growth	*Petersenia*, *Olpidiopsis* spp.	Li *et al*. (2010); Klochkova *et al*. (2011); Badis *et al*. (2018); Badis *et al*. (2019)
Ceramiales – various	Chytrids	Not detailed	*Chytridium* spp.	Li *et al*. (2010)
Bangiales: Bangiaceae				
Pyropia spp. (nori)	Red-rot disease	Bleaching or other colour changes, red dots, lesions and holes in blades, mortality	Oomycete *Pythium* spp., Ascomycete *Alternaria* sp.	Kim *et al*. (2014); Bernard (2018); Ward *et al*. (2019); Behera *et al*. (2022a); Sugumaran *et al*. (2022)
Pyropia spp.	Olpidiopsis disease, 'Chytrid blight'	Bleached sections, greenish lesions, blade decay	Oomycete *Olpidiopsis* spp. (causative agent originally thought to be a chytrid)	Kim *et al*. (2014); Bernard (2018); Ward *et al*. (2019); Behera *et al*. (2022a)
Pyropia spp.	White spot disease	Bleaching and mortality of conchelis stage	Ascomycetes *Phoma*, *Alternaria* spp.	Kim *et al*. (2014); Ward *et al*. (2019); Behera *et al*. (2022a); Murua *et al*. (2023)
Pyropia spp.	Suminori disease	Cell damage, colour change, reduced product value	Bacteria *Gaetbulibacter saemankumensis*, *Flavobacterium*	Mine *et al*. (2009); Egan *et al*. (2014); Hudson and Egan (2022)
Pyropia spp.	Green-spot disease, anaaki disease	Lesions with green borders, secondary bacterial infections, blade becomes slimy and rots	PyroV1 virus, Bacteria *Flavobacterium*, *Pseudomonas* and *Vibrio* spp.	Kim *et al*. (2014); Ward *et al*. (2019); Behera *et al*. (2022a); Hudson and Egan (2022); Sugumaran *et al*. (2022)
Pyropia spp.	White blight	Bleached areas, cell lysis	Unknown	Kim *et al*. (2014); Ward *et al*. (2019); Behera *et al*. (2022a)

Taxon/taxa affected	Disease/issue common name	Disease symptoms/impacts	Pest or pathogen(s) involved	Key references
Pyropia spp.	Diatom felt	Dirty appearance, bleaching, reduced growth and product quality	Diatoms *Fragellaria* sp., *Licmophora flabellata*, *Melosira* sp., *Navicula* sp.	Kim *et al*. (2014); Ward *et al*. (2019); Behera *et al*. (2022a)
Pyropia spp.	Cyanobacteria felt	Felt-like covering, blade degeneration, often occurs simultaneously with green-spot disease	Cyanobacteria	Kim *et al*. (2014); Bernard (2018)
Palmariales: Palmariaceae				
Palmaria palmata	Oomycetes	Performations in thalli, destruction of tetraspores	*Olpidiopsis* spp.	Badis *et al*. (2018); Badis *et al*. (2019)
Palmaria mollis	Oomycetes	Not detailed	*Petersenia palmariae*	Li *et al*. (2010)
Corallinales				
Coralline algae including *Porolithon onkodes*	Coralline lethal orange disease	bright orange dots progressing to tissue necrosis and mortality	*Planoccocus*, *Bacillus*, *Pseudomonas*	Neill *et al*. (2008); Egan *et al*. (2014)
Rhodophyta	Bacterial disease	Galls and proliferating tissue	unidentified bacteria	Neill *et al*. (2008)
Rhodophyta	Brown algal endophytes	Not detailed	*Microspongium tenuissimum*, *Myriotrichia* spp.	Burkhardt and Peters (1998); Neill *et al*. (2008)
Rhodophyta (*Palamaria*, *Osmundea*)	Epiphytes	Reduced production and product quality	Brown and green seaweed including *Ectocarpus*, *Ulva* spp.	Kerrison *et al*. (2016)
Laminariales – various				
Laminariales (*Saccharina*, *Laminaria*, *Alaria*)	Stipe blotch disease	Tissue necrosis and reduced growth	Ascomycete *Phycomelaina laminariae*	Neill *et al*. (2008)
Laminariales (*Egregia*, *Saccharina*, *Laminaria*)	Unnamed	Lesions, black patches, stipe damage	Ascomycetes *Pontogeneia erikae*, *Sigmoidea marina*, *Ophiobolus laminariae* Oomycete *Petersenia* spp.	Neill *et al*. (2008)
Laminariales (*Alaria*, *Nereocystis*, *Saccharina*, *Laminaria*, *Lessonia*, *Macrocystis*, *Ecklonia*)	Brown endophyte diseases	brown spots, warts, galls, stipe deformation, increased risk of thallus detachment	Endophytic brown algae including *Laminariocolax* and *Microspongium* spp.	Burkhardt and Peters (1998); Neill *et al*. (2008); Murúa *et al*. (2019)
Laminariales (*Saccharina*, *Laminaria*, *Eisenia*, *Pterygophora*, *Macrocystis*, *Alaria*)	Grazing	Amphipods bore into stipes, mortality may result	Amphipods including *Peramphithoe* and *Amphitholina* spp.	Neill *et al*. (2008)
Laminariales (*Saccharina*, *Laminaria*, *Ecklonia*, *Undaria*)	Unnamed	Abnormal gametophyte growth	Phycodnaviridae double stranded DNA viruses	McKeown *et al*. (2017); McKeown *et al*. (2018); Behera *et al*. (2022a); (Sugumaran *et al*. 2022)
Laminariales: Laminariaceae				
Saccharina japonica (kombu)	Red spot	Bacterial growth on culture ropes causes young sporelings to detach	Bacteria *Alteromonas* spp. *Pseudoalteromonas* spp.	Sawabe *et al*. (1998); Campbell *et al*. (2014); Egan *et al*. (2014); Ward *et al*. (2019); Behera *et al*. (2022a)
Saccharina japonica	Hole-rotten disease	Holes, thallus decay, detachment of sporelings from culture ropes	Bacteria *Pseudoalteromonas* spp., *Vibrio* spp., *Halomonas* spp.	Wang *et al*. (2007); Egan *et al*. (2014); Ward *et al*. (2019); Behera *et al*. (2022a)

Taxon/taxa affected	Disease/issue common name	Disease symptoms/impacts	Pest or pathogen(s) involved	Key references
Saccharina japonica	Green rot, falling-off disease	Stipe turns green and decays, sporelings detach from culture ropes	Bacteria *Pseudomonas* spp.	Wang *et al*. (2014); Ward *et al*. (2019); Behera *et al*. (2022a)
Saccharina japonica	Spot-wounded fronds	Not detailed	Bacteria Pseudoalteromonas elyakovii	Egan *et al*. (2014)
Saccharina japonica	Malformation disease	Abnormal zygote development, mortality of sporelings	Bacteria *Macrococcus* sp.	Wang *et al*. (2014); Ward *et al*. (2019); Behera *et al*. (2022a)
Saccharina japonica	Twisted frond disease	Deformed fronds, short holdfasts	Mycoplasma-like organisms	Wang *et al*. (2014); Ward *et al*. (2019); Behera *et al*. (2022a)
Saccharina japonica	White spot disease	White or yellow lesions, blisters, reduced growth, altered biochemical content	Unknown	Wang *et al*. (2021)
Saccharina japonica	Gametophyte disease	Swollen, bleached gametophytes	Bacteria *Alteromonas* sp.	Egan *et al*. (2014)
Saccharina japonica	Biofouling	Decreased growth, product quality	Hydroids including *Obelia geniculata*, Bryozoa including *Membranipora membranacea*, algae, polychaetes, caprellids and oysters	Kim *et al*. (2017); Bernard (2018); Behera *et al*. (2022a)
Saccharina religiosa	Unnamed	Lesions, thallus bleaching	Bacteria *Alteromonas* sp.	Vairappan *et al*. (2001); Egan *et al*. (2014); Sugumaran *et al*. (2022)
Nereocystis luetkeana	White rot	Stipe rots and becomes covered in white slime	Bacteria *Acinetobacter* sp.	Neill *et al*. (2008)
Laminariales: Alariaceae				
Undaria pinnatifida (wakame)	Shot hole disease	Brown spots near midrib, spreading to pinnate parts of blade	Bacteria *Aeromonas*, *Flavobacterium*, *Moraxella*, *Pseudoalteromonas*, *Vibrio*	Neill *et al*. (2008); Behera *et al*. (2022a)
Undaria pinnatifida	Spot decay	Not detailed	Bacteria *Halomonas venusta*	Behera *et al*. (2022a)
Undaria pinnatifida	Green decay	Small holes with green margins, blade decays	Bacteria *Vibrio logei*	Neill *et al*. (2008); Behera *et al*. (2022a)
Undaria pinnatifida	Pin-hole disease	Damage by nauplii of harpacticoid copepods that graze on the blade	Copepods *Amenophia orientalis*, *Parathalestris infestus*, *Scuttelidum* sp., *Tahlestris* sp.	Neill *et al*. (2008); Behera *et al*. (2022a)
Undaria pinnatifida	Chytrid blight	Colour loss, thallus decay	Oomycete *Olpidiopsis* sp.	Neill *et al*. (2008); Bernard (2018)
Undaria pinnatifida	Grazing	Hole bored through stipe, sometimes causing thallus to break and detach	Isopod *Cymodocea japonica*	Neill *et al*. (2008); Sugumaran *et al*. (2022)
Undaria pinnatifida	Brown endophytic disease	Galls, thallus deformation. Thalli become thick and stiff, reduced market value	Endophytic brown algae *Laminariocolax*, *Laminarionema*	Neill *et al*. (2008); Bernard (2018); Behera *et al*. (2022a)
Laminariales: Lessoniaceae				
Ecklonia radiata (golden kelp)	Grazing	Amphipod burrowing into stipe leading to frond mortality, secondary viral infections	Amphipod *Orchomenella aahu*	Neill *et al*. (2008)
Ecklonia radiata	Bleaching	Bleached areas, reduced photosynthetic performance, possibly associated with die-backs in wild populations	Single-stranded DNA viruses	Easton *et al*. (1997); Marzinelli *et al*. (2015); Beattie *et al*. (2018)
Fucales – various				

Taxon/taxa affected	Disease/issue common name	Disease symptoms/impacts	Pest or pathogen(s) involved	Key references
Fucales (*Fucus*, *Saccorhiza*, *Cystoseira*)	Unnamed	Galls, thallus deformation and degradation	Bacteria including *Pseudoalteromonas*	Neill *et al*. (2008)
Fucales (*Sargassum*, *Fucus*)	Unnamed	Tissue degradation	Amoeba	Neill *et al*. (2008)
Fucales (*Cystophora*, *Cystoseia*, *Halydris*, *Sargassum*)	Fungal infection	Galls	Ascomycetes including *Massarina* and *Haloguignardia* spp.	Neill *et al*. (2008)
Fucales (*Cystoseira*, *Halidrys*, *Sargassum*)	Mitosporic fungi	Infection of galls leading to ruptures of gall tissue	Ascomycete *Sphaceloma cecidii*	Li *et al*. (2010)
Fucales (*Ascophyllum*, *Fucus*, *Cystoseira*, *Cystophora*, *Hormosira*, *Xiphophora*)	Endophytes	Galls. Some endophytes associated with damaged tissue but may occur secondary to damage rather than being causative	Seaweed including red: *Polysiphonia*, *Vertebrata*; brown: *Elachista*, *Laminariocolax* and other Ectocarpales; green *Ulvella* and *Entocladia* spp.	Neill *et al*. (2008); Longtin and Scrosati (2009)
Fucales: Durvilleaceae				
Durvillea spp. (bull kelp)	Galls	Yellowish galls on sporophytes, possibly impacting structure. Infection of gametophytes may reduce reproductive output	Phytomyxea *Maullinia* spp.	Goecke *et al*. (2012); Murua *et al*. (2017); Mabey *et al*. (2021)
Fucales: Fucaceae				
Fucus spp.	Galls	Galls	Nematodes *Halenchus* spp.	Neill *et al*. (2008)
Fucales: Sargassaceae				
Sargassum spp.	Grazing	Not detailed	Isopod *Cymodoce japonica*	Sugumaran *et al*. (2022)
Ectocarpales	Oomycetes	Abnormal growth	*Eurychasma*, *Sirolpidium* spp.	Li *et al*. (2010)
Ectocarpales	Chytrids	Mortality in wild populations	*Chytridium polysiphoniae*	Li *et al*. (2010)
Ectocarpales	Viral infections	Tissue necrosis, failure of zoospores to germinate	Phycodnaviridae double stranded DNA viruses	Neill *et al*. (2008); McKeown *et al*. (2017); McKeown *et al*. (2018)
Bryopsidales: Caulerpaceae				
Caulerpa lentillifera (sea grapes)	Unnamed	Colour change from green to pinkish-red, necrosis and detachment of infected areas	Unknown, possible Bacteroidota or Proteobacteria	Liang *et al*. (2019)
Ulvales: Ulvaceae				
Ulva spp. (sea lettuce)	Perforation disease, degradation disease	Green spots, enlarging into lesions and holes. Stunted growth, frond deformation and tissue loss	Green endophyte *Ulvella* spp	Colorni (1989); del Campo *et al*. (1998)
Ulva spp. (sea lettuce)	Bleaching	Bleaching, necrosis	RNA viruses	van der Loos *et al*. (2023)
Ulva lactuca	Grazing	Reduced productivity and product value	Gastropod *Littorina* sp.	Kerrison *et al*. (2016)
Cladophorales	Oomycetes	Colour change, particularly from green to brown, loss of chlorophyll, reduced growth	*Sirolpidium* spp.	Li *et al*. (2010)
Chlorophyta (Bryopsidales, Cladophorales, Ulvales)	Chytrids	Colour change, reduced growth	Coenomyces, Olpidium, Rhizophydium	Li *et al*. (2010)

Water mould (oomycete) infections

Water moulds or oomycetes are fungus-like microscopic eukaryotic pathogens (Derevnina *et al*. 2016). Oomycetes have previously been regarded as fungi or protists, but are currently placed in the phylum Oomycota in kingdom Chromista,[3] which also contains the brown seaweeds (phylum Ochrophyta). Water moulds are important parasitic pathogens of plants, including many food crops, and animals, including farmed fish, as well as of seaweeds (Li *et al*. 2010; Derevnina *et al*. 2016; Klochkova *et al*. 2016; Schwelm *et al*. 2018). Water moulds are among the best-studied seaweed pathogens, but genetic and ultrastructure studies are only just beginning to reveal diversity and phylogenetic relationships within Oomycota. Several seaweed-infecting holocarpic oomycetes that were originally identified as *Olpidiopsis* are now known to not be closely related to the type species of this genus, and their scientific names require updating (Buaya *et al*. 2019; Buaya *et al*. 2021; Zuccarello *et al*. 2024). Transfer of these *Olpidiopsis* to the genus *Pontisma* has been proposed (Buaya *et al*. 2019; Buaya *et al*. 2021), but suggested topologies lack support, and hence retention of the species in *Olpidiopsis* is recommended until taxonomy of the seaweed-infecting holocarpic oomycetes is clarified (Zuccarello *et al*. 2024). Other water mould genera that infect seaweeds are *Pythium*, *Petersenia* and *Eurychasma.*

Water mould infections spread via motile zoospores, which may be carried in water or on equipment, as well as on infected seaweeds (Klochkova *et al*. 2011; Klochkova *et al*. 2016; Craigie *et al*. 2019). The zoospores of *Olpidiopsis* and *Pythium* spp. remain infective for several days in seawater (Klochkova *et al*. 2011; Klochkova *et al*. 2016), and *Pythium* spp. also produce resting cysts (Klochkova *et al*. 2016). Most seaweed-infecting oomycetes are obligate parasites (Gachon *et al*. 2009; Li *et al*. 2010; Klochkova *et al*. 2011), but *Pythium* spp. can persist for long periods as a saprophyte on decaying plant and algal material (Klochkova *et al*. 2016).

Seaweeds known to host water mould infections include red seaweeds of the orders Bangiales (which includes nori), Bonnemaisoniales (which includes *Asparagopsis*), and Ceramiales; green seaweeds of the Bryopsidales; and brown seaweeds of the Ectocarpales and Laminariales (which includes golden kelp). Water mould infections are a serious issue in cultivation of nori (Kim *et al*. 2014; Badis *et al*. 2018) and also impact cultivation of other red seaweeds (Badis *et al*. 2018; Craigie *et al*. 2019), and are believed to be responsible for large die-offs in wild stocks of Ectocarpales (Li *et al*. 2010). In Laminariales, water moulds can infect the gametophyte stage and can cause losses of gametophyte cultures or failure of string seeding, and infections of wakame sporophytes have also been recorded and noted to result in losses of young seedlings (Neill *et al*. 2008). Infections have not been specifically noted in golden kelp but should be considered possible. In *Asparagopsis* and the related *Bonnemaisonia hamifera*, an *Olpidiopsis* sp. infects tetrasporophytes in wild populations and destroys tetraspores (Fletcher *et al*. 2015), and thus may reduce reproductive output.

Water moulds cause two major diseases impacting nori production: red rot (caused by *Pythium* spp.) and Olpidiopsis blight (caused by *Olpidiopsis* spp.). Red rot disease (Figure 1) is known from nori farms in China, Japan and Korea, and the disease has also been detected in wild nori in the Netherlands and New Zealand (Kim *et al*. 2014; Lee *et al*. 2015; Diehl *et al*. 2017). In farmed nori, blades infected by red rot can decay within a few days, and outbreaks lead to crop losses of up to 20% within a farming area, and complete loss of the production cycle for individual farms (Kim *et al*. 2014). Olpidiopsis blight (Figure 2) is known from nori farms in China, Japan and Korea, wild nori and other Bangiales in Scotland (Klochkova *et al*. 2011; Kim *et al*. 2014; Badis *et al*. 2018). Outbreaks of Olpidiopsis blight can cause losses of about 25% of stock in a farming area, and lead to production delays or require early harvest to prevent spread (Kim *et al*. 2014).

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[3] Other classification schemes for eukaryotes have been proposed that use different names and terminology, but group water moulds with the same taxa as the classification of WoRMS, i.e., with the brown seaweeds and in a supergroup containing alveolates and rhizarians, rather than with fungi or protozoa. Other names for the clade including the water moulds and brown seaweeds are Stramenopiles, Straminipila, or Heterokonta.

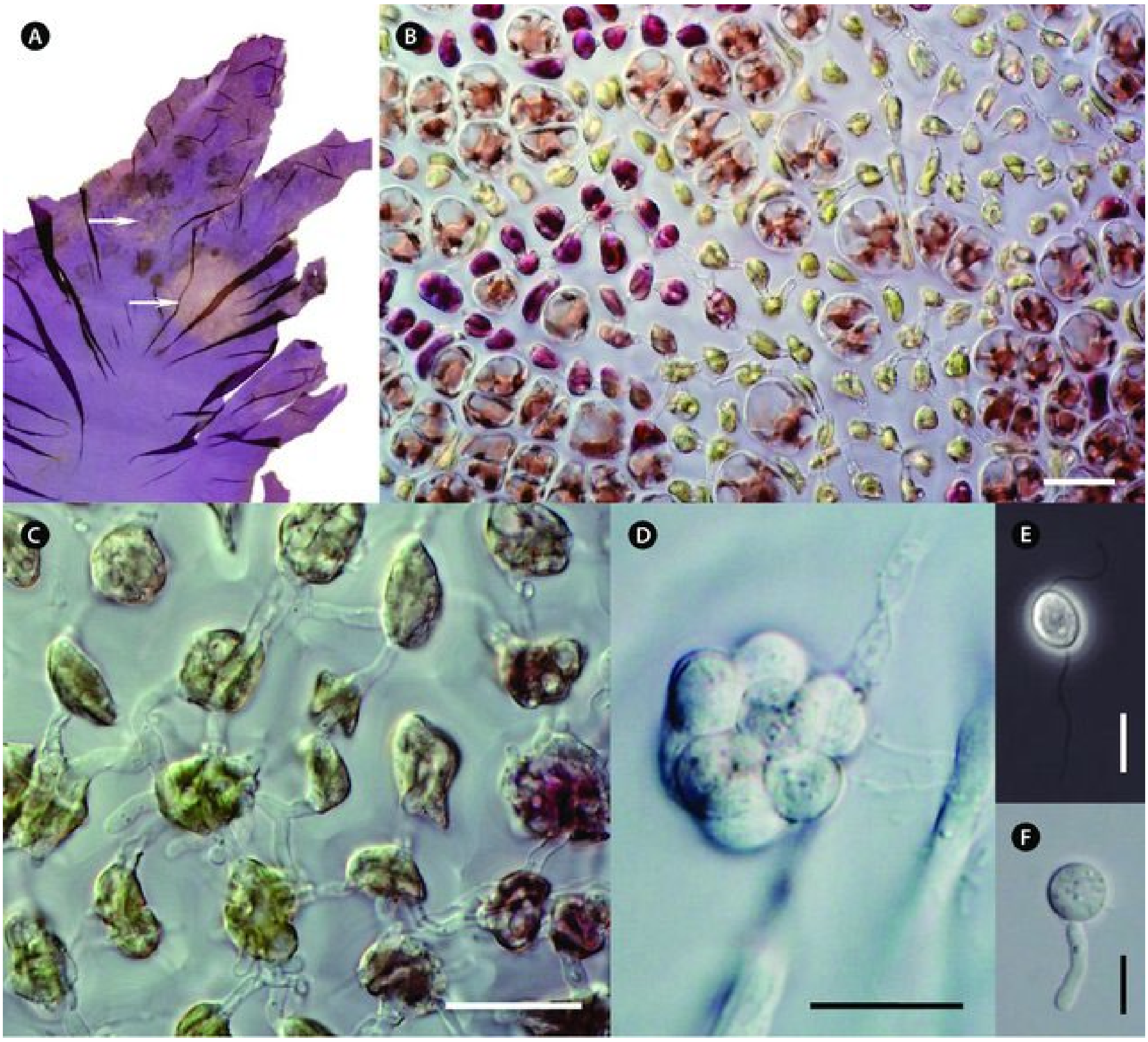

Figure 1. Red-rot disease in commercially cultivated *Pyropia* in Korea. (A) Infected host blade. Areas on the blade destroyed by the infection are indicated by arrows. (B and C) Enlarged images of the blade infected with *Pythium porphyrae* mycelium. Only a few uninfected host cells remain. (D) *P. porphyrae* zoosporangium. (E) Biflagellate motile zoospore of *P. porphyrae*. (F) Germinating zoospore of *P. porphyrae* with germ tube. Scale bars represent: B – 50 µm; C and D – 10 µm; E and F – 5 µm. Reproduced from Kim *et al*. (2014).

Water moulds that infect seaweeds typically demonstrate low host specificity (Gachon *et al*. 2009; Li *et al*. 2010; Klochkova *et al*. 2011; Klochkova *et al*. 2016), with infection by *Olpidiopsis*/*Pontisma* occurring across many orders of red seaweed and *Eurychasma* occurring in both Ectocarpales and Laminariales (Gachon *et al*. 2009; Klochkova *et al*. 2011; Timanikova *et al*. 2024). *Olpidiopsis* have also been recorded in some brown seaweeds and *Eurychasma* in some reds, with both genera also recorded in a few green seaweed species (Timanikova *et al*. 2024). *Pythium* spp. can infect multiple Bangiales spp. (Diehl *et al*. 2017) and *Petersenia lobata* can infect several Ceramiales (Li *et al*. 2010). Severity of infection varies between species, with little impact of infection observed in some species, while others suffer rapid, high mortality (Gachon *et al*. 2009; Klochkova *et al*. 2011). Susceptibility to infection can also vary between different geographic strains of the same seaweed (Li *et al*. 2010). Korean water mould strains have been shown to cause disease in European-cultivated nori and *vice versa*, however, demonstrating that oomycete pathogens introduced from different geographic areas can pose significant risk (Badis *et al*. 2018). Some water mould species may be relatively host-specific, e.g., *Petersenia palmariae* that infects *Palmaria* spp. was not found to infect other red seaweeds (Li *et al*. 2010).

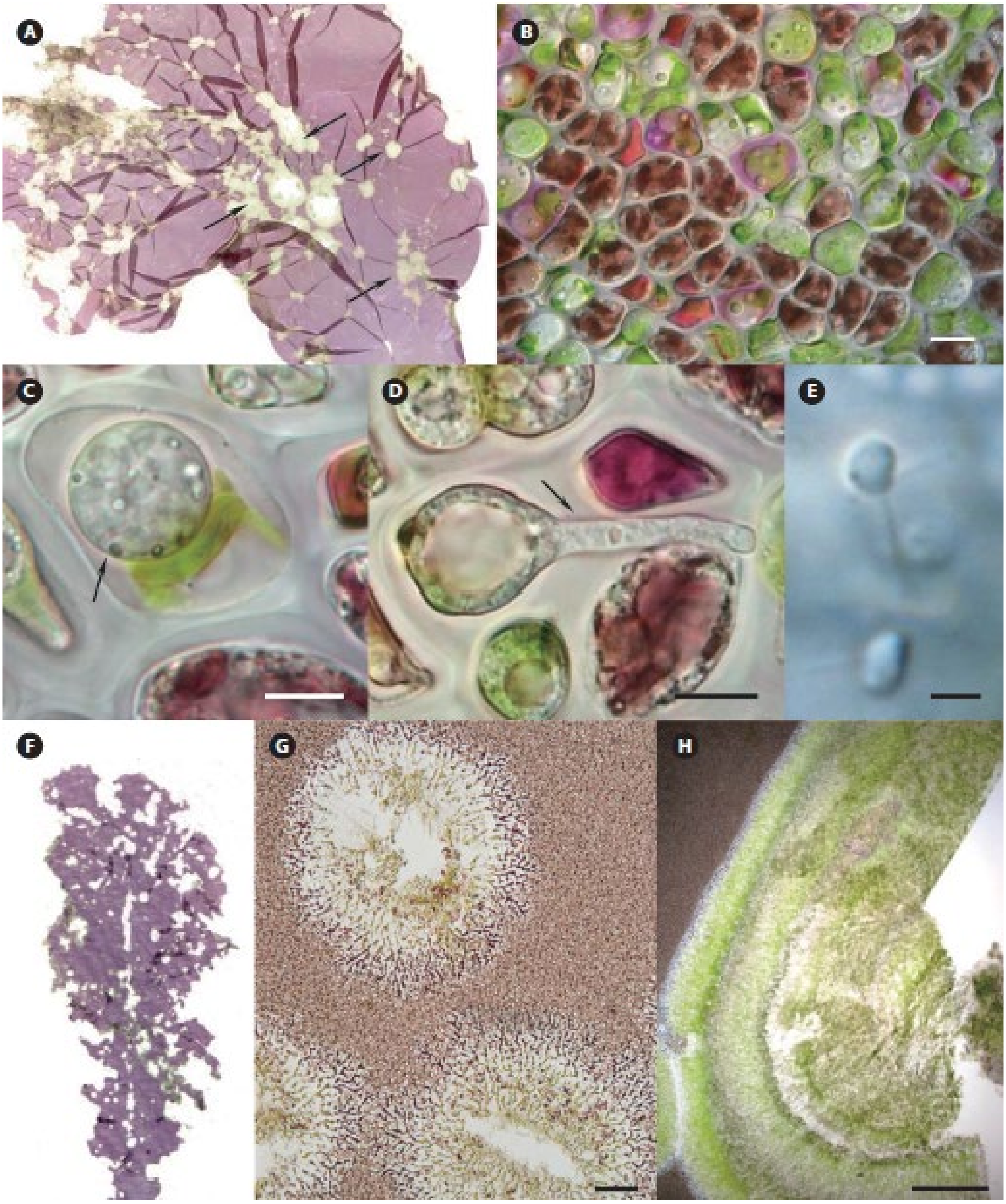

Figure 2. Typical symptoms of *Olpidiopsis* (A-E) and green-spot diseases (F-H) in commercially cultivated *Pyropia* in Korea. (A) *Olpidiopsis* sp.-infected host blade. Areas on the blade destroyed by the infection are indicated by arrows. (B) Enlarged image of the infected blade, with many *Olpidiopsis* zoosporangia. Only a few uninfected host cells remain. (C) Parasitic thallus (arrow) inside the host cell. (D) Large central vesicle develops inside the mature zoosporangium to push out the liberation tube (arrow) for the release of zoospores. (E) Biflagellate motile spores of *Olpidiopsis*. (F) Green-spot disease-infected blade with numerous lesions. (G) Typical appearance of lesions that look like shot holes on the contaminated blade. (H) Enlarged image of the deteriorating blade, showing wide green coloured border of the lesion. Scale bars represent: B – 50 µm; C and D – 10 µm; E – 2 µm; G – 100 µm; H – 500 µm. Reproduced from Kim *et al*. (2014).

Bacterial, fungal and protist diseases

Bacteria, fungi and protists (e.g., amoebae) have all been implicated as causative agents of seaweed diseases. Common signs of seaweed diseases caused by bacteria, fungi and protists are similar to those caused by oomycetes, and include colour changes, particularly bleaching (Figures 3 and 4), and thallus decay, often beginning with small holes or lesions (Li *et al*. 2010; Ward *et al*. 2019; Faisan *et al*. 2021; Behera *et al*. 2022a; Sugumaran *et al*. 2022). Bacterial infections can also cause proliferating, tumor-like growths in seaweed (Neill *et al*. 2008; Egan *et al*. 2014; Murua *et al*. 2023).

Figure 3. Bleached thallus of *Kappaphycus malesianus* caused by ice-ice syndrome. (a) Endophytes *Melanothamnus* sp. covering rotten bleached thallus of *K. malesianus*. (b) Bleached *K. malesianus* with 70% epi-endophyte coverage. Scale bar: 3 cm. Reproduced from Kambey *et al*. (2021c).

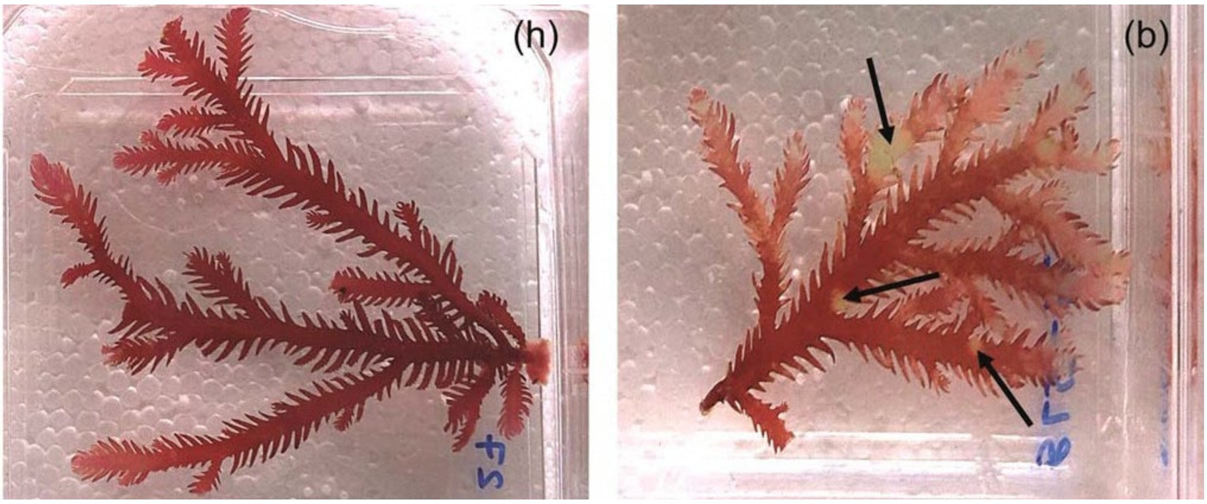

Figure 4. Bleaching of *Delisea pulchra* after inoculation with candidate pathogens showing healthy (h) and bleached (b) specimens during an *in vivo* infection assay. Arrows point to areas of bleached (diseased) tissue. Reproduced from Kumar *et al*. (2016).

The phyla Bacteroidota, Alphaproteobacteria and Gammaproteobacteria contain many species implicated as causative agents in seaweed diseases (Wang *et al*. 2007; Egan *et al*. 2014; Kumar *et al*. 2016; Syafitri *et al*. 2017; Ward *et al*. 2021; Hudson and Egan 2022). Not all bacteria belonging to these groups, however, cause disease. Several Bacteroidota are involved in mutualistic or commensal relationships with host organisms, including facilitating development in some green algae (Hudson and Egan 2022; Li *et al*. 2023), while many Gammaproteobacteria and some Bacteroidota are protective against seaweed diseases, including some from the same genera (e.g., *Vibrio*, *Pseudoalteromonas*, *Gaetbulibacter*) as pathogenic strains (Saha *et al*. 2019; Li *et al*. 2022; Li *et al*. 2023). Traits of pathogenic bacterial strains, which occur across taxonomic groups, include adhesion factors that facilitate host colonisation, resistance to oxidative stress, and the ability to degrade or metabolise seaweed cell walls (Egan *et al*. 2014; Wang *et al*. 2014).

Fungi, including Ascomycota and Chytridiomycota, are also associated with seaweed disease, but as with bacteria, not all seaweed associated fungi are pathogenic. Several fungi of seaweeds may appear to be pathogenic due to their endophytic nature but at least some can protect against disease due to production of metabolites with antibacterial and antioomycete activity (Murua *et al*. 2023). For example, several Ascomycota found on brown algal hosts show the potential to inhibit pathogens, including oomycetes and Phytomyxea (Li *et al*. 2023). Ascomycota occurrence in *Caulerpa* is associated with healthy rather than diseased specimens and these Ascomycota are probably symbiotic (Liang *et al*. 2019). Ascomycota do, however, cause a disease similar to red rot (Mo *et al*. 2015) and losses of the conchocelis stage in nori aquaculture (Kim *et al*. 2014; Murua *et al*. 2023), can induce bleaching and necrosis in jellyweeds (Tahiluddin and Terzi 2021), and cause galls on some brown algae that are then secondarily infected by other fungi (Neill *et al*. 2008; Li *et al*. 2010). Chytridiomycota (chytrids) associated with *Gracilariopsis* sp. cultivation do not appear to cause disease, but other chytrids are reported to be pathogenic, particularly in Ectocarpales, where they may be responsible for widespread mortality in wild populations (Li *et al*. 2010). Chytrids also cause disease in wild populations of red and green seaweeds (Li *et al*. 2010).

Bleaching and thallus decay in Gracilariales and Laminariales may also be induced by infection by endophytic amoebae (Correa and Flores 1995; Neill *et al*. 2008).

Most bacterial, fungal and protist diseases of seaweed appear to be environmentally mediated, and to be caused by opportunistic pathogenic strains that infect seaweeds in the presence of stressors such as unsuitable light or temperature, or following physical damage (Campbell 2011; Hudson and Egan 2022; Li *et al*. 2022; Murua *et al*. 2023). Many bacteria demonstrated to be pathogenic by inoculation experiments are opportunistic and are common on healthy seaweeds, although they proliferate on diseased specimens (Weinberger *et al*. 1997; Wang *et al*. 2014; Kumar *et al*. 2016; Ling *et al*. 2022). Disease leads to changes in the microflora of affected seaweeds (Qiu *et al*. 2019; Ling *et al*. 2022), but of the bacteria that proliferate on diseased seaweeds, only a subset cause disease (Vairappan *et al*. 2001; Wang *et al*. 2007; Kumar *et al*. 2016; Syafitri *et al*. 2017).

Seaweed microbiomes play an important role in seaweed health and disease resistance (Weinberger *et al*. 1997; Qiu *et al*. 2019; Ling *et al*. 2022; Li *et al*. 2023). Excluding opportunistic pathogens from cultivation is likely to be impractical due to the prevalence of these strains, and because there is a risk of disrupting the seaweed microbiome and depleting strains that may be protective against epiphytes or pathogens (Weinberger *et al*. 1997; Li *et al*. 2023). Maintaining suitable abiotic conditions is important to reduce the risk from opportunistic pathogens, but biosecurity measures are still useful to limit the spread and impact of disease caused by opportunistic pathogens where this occurs (Mateo *et al*. 2020; Kambey *et al*. 2021a; Kambey *et al*. 2021c). Pathogenic strains typically proliferate on diseased tissue, hence measures such as removing or isolating diseased stock will prevent or limit the exposure of healthy seaweeds to high pathogen loads that could promote disease.

Data on host specificity of fungal and bacterial seaweed pathogens are lacking given that few of these pathogens have been well characterised. Seaweed microbiomes vary between taxa as well as seasonally and geographically (Egan *et al*. 2013; Marzinelli *et al*. 2015). Related seaweeds typically have microbiomes that are similar across disparate locations, while microbiomes differ between co-occurring unrelated seaweeds, suggesting host specificity of many seaweed-associated bacteria (Egan *et al*. 2013). This is supported by the fact that few specific bacteria have been isolated from multiple seaweed species (Hollants *et al*. 2013). Some bacterial strains do, however, occur across several seaweed taxa (Egan *et al*. 2013; Hollants *et al*. 2013).

Seaweed host genotype and health status strongly influence differences in the microbiome within a species (Marzinelli *et al*. 2015; Wood *et al*. 2022; Vadillo Gonzalez *et al*. 2023). Variation in microbiomes of a species also occurs seasonally and between habitats within an area, demonstrating the importance of environmental factors in influencing the seaweed microbiome (Egan *et al*. 2013; Aires *et al*. 2016).

Viral diseases

A diverse range of viruses infect marine algae with important ecological effects, including the ability to lyse bloom-forming microalgae (Gachon *et al*. 2010; Coy *et al*. 2018), but seaweed viruses are relatively poorly studied (Gachon *et al*. 2010; Lachnit *et al*. 2015; Coy *et al*. 2018; Murua *et al*. 2023). The best known viruses of seaweeds belong to the family Phycodnaviridae, which is one of the most diverse groups of marine DNA viruses, comprising approximately 150 described viruses (Schroeder and McKeown 2021). Other viruses detected in seaweeds include circular rep-encoding single-stranded (CRESS) DNA viruses, and RNA viruses belonging to the *Durnavirales* and *Picornavirales* (Lachnit *et al*. 2015; Schroeder and McKeown 2021; van der Loos *et al*. 2023). In some cases, viruses found in seaweeds could be hosted by seaweed-associated fungi rather than by the seaweed itself (Schroeder and McKeown 2021). New seaweed viruses are being discovered frequently, even in relatively small studies, highlighting that there is likely high undiscovered diversity in seaweed viruses (van der Loos *et al*. 2023; Dekker *et al*. 2024).

Although viruses are known to infect many seaweeds, their role as causative agents in seaweed diseases is unclear. In brown seaweeds, viruses are implicated in bleaching and die-backs of wild populations, including of golden kelp (Easton *et al*. 1997; McKeown *et al*. 2017; Beattie *et al*. 2018; McKeown *et al*. 2018). The role of viruses in causing disease or mortality in kelp is not, however, established (Murua *et al*. 2023). Phaeoviruses, Phycodnaviridae that infect brown seaweeds, appear to typically occur at high prevalence but to have limited impact on infected hosts, particularly in Laminariales (Schroeder and McKeown 2021). Newly discovered RNA viruses in winged kelp (*Alaria*) and *Saccharina* spp. (Laminariales) were similarly common but not clearly associated with disease occurrence (Dekker *et al*. 2024). In Ectocarpales, phaeoviruses may reduce growth and photosynthesis, and can reduce reproductive output or result in sterility. Phaeoviruses may also cause reduced reproductive output or gametophyte failure in Laminariales (Neill *et al*. 2008). Unlike Laminariales, Ectocarpales can reproduce asexually; this capacity is maintained in infected seaweeds (Schroeder and McKeown 2021).

In red seaweeds, a chloroplast RNA virus, termed PyroV1, is recognised as the primary cause of green-rot disease (Figure 2), an important disease of cultivated nori (Kim *et al*. 2016; Murua *et al*. 2023). Many other viruses have been isolated from red seaweeds, but, as with viruses of brown seaweeds, they often occur without apparent detrimental effects on the host (Benites and Alves-Lima 2022). RNA viruses isolated from the red seaweed *Delisea pulchra* show taxonomic affinity to the microalgal viruses that lyse phytoplankton, but their impact on *D. pulchra* is unknown (Lachnit *et al*. 2015). In addition to green-rot disease of nori, red seaweed viruses may be responsible for gall formation and proliferating growths in some taxa (Benites and Alves-Lima 2022).

Viruses of green seaweeds are particularly poorly known (Schroeder and McKeown 2021). Recent studies have, however, identified a diversity of viruses, including CRESS DNA and *Picornavirales*-like RNA viruses, from sea lettuce (van der Loos *et al*. 2023). The CRESS and picorna-like viruses were found to be associated with bleaching, but it is unclear whether these viruses are causative or simply proliferate in bleached tissue caused by another pathogen or abiotic conditions (van der Loos *et al*. 2023).

The PyroV1 virus causes cells to lyse, releasing infective particles that infect and lyse neighbouring cells, causing spreading lesions that are then infected by bacteria (Kim *et al*. 2016). The infectious particles released from lysed cells can also infect tissue of other individuals, with damaged areas more susceptible than intact blades (Kim *et al*. 2016). Phaeoviruses appear to be transmitted primarily vertically (i.e., directly from one generation to the next) but also produce virions that enable the horizontal spread of infection (i.e., between individuals) (Schroeder and McKeown 2021).

Dynamics of Phaeovirus infection of brown seaweed hosts differ from typical host-virus systems; notably, many Phaeoviruses infect seaweeds across a range of taxa (e.g., both Ectocarpales and Laminariales) rather than being host-specific (Schroeder 2015). Other seaweed-associated viruses show greater specificity than phaeoviruses and infect limited taxa within a genus or order (Gachon *et al*. 2010; McKeown *et al*. 2018). The PyroV1 virus responsible for green-rot disease in cultivated nori infects multiple Korean nori species (genus *Pyropia*) but does not infect the conchocelis stage (Kim *et al*. 2016). PyroV1 also does not infect other taxa of red algae or nori species from Australia (*Pyropia* spp.) and New Zealand (*Porphyra* spp.) (Kim *et al*. 2016; Benites and Alves-Lima 2022).

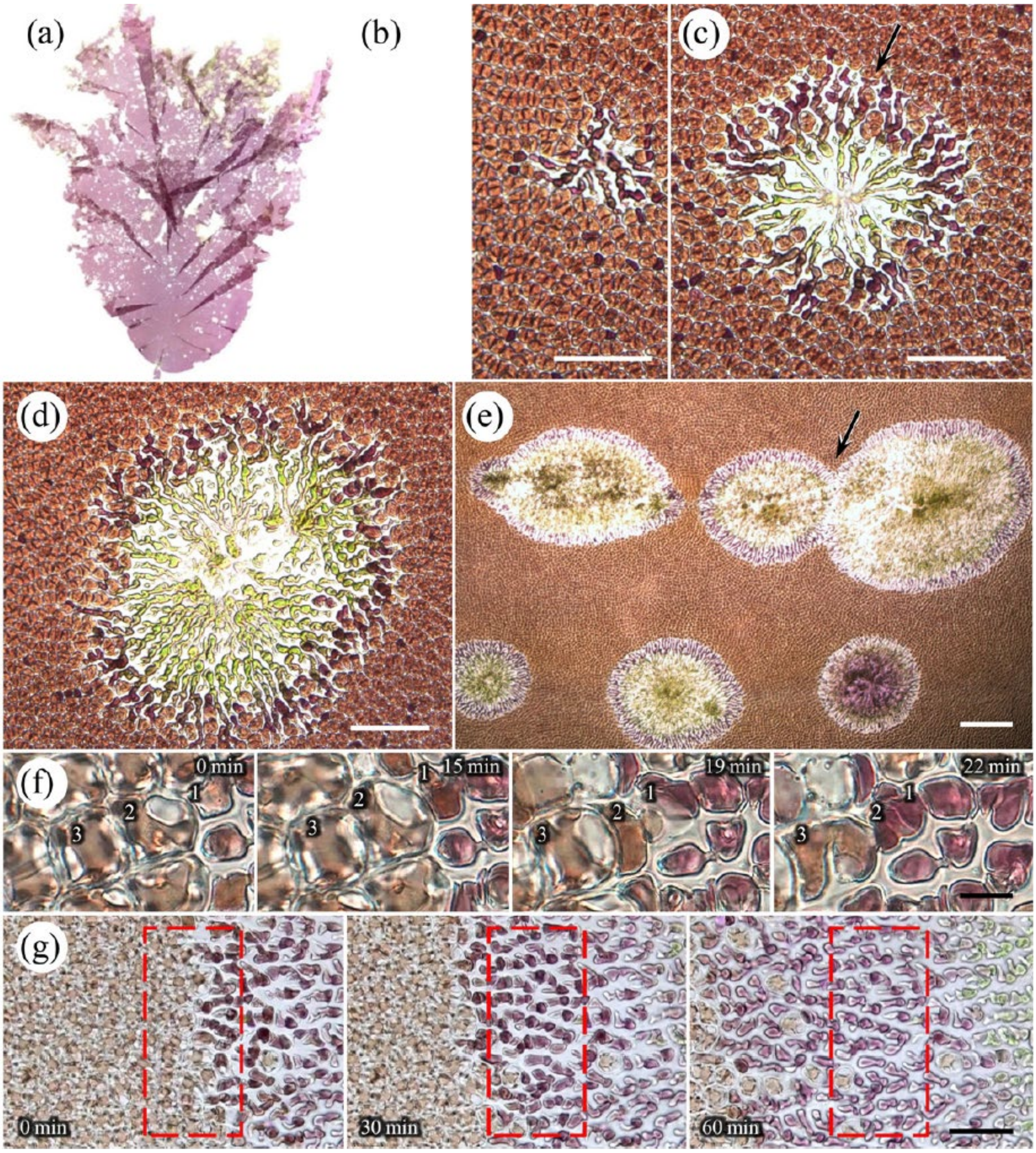

Figure 5. Typical symptoms of green-spot disease infection in commercially cultivated *Pyropia* in Korea. (a) Infected blade with numerous lesions that look like bullet holes. (b) A small lesion at the initial stages of infection, showing green centre. (c) Upon progression of infection, a chain of pinkish cells develops encircling the green lesion. Viruses were observed in the cells contacting the pinkish lesion border (arrow). (d–e) The lesion enlarges over time and merges with neighbouring lesions, forming bigger holes on the blade (arrow). (f) Time-lapse photography of the progression of infection. It took 15 minutes for one infected cell (marked as 1) to collapse; the neighbouring cell (marked as 2) collapsed seven minutes later. (g) Approximately 150-200 μm-long portion of blade dies off within one hour (compare the red set frames). Scales: b-d – 40 μm, e – 200 μm, f – 10 μm, j – 50 μm. Figure reproduced from Kim *et al.* (2016).

Seaweed pests

Seaweeds, both wild and farmed, host many algal and invertebrate species, including epiphytic microalgae and seaweeds, gastropods, polychaetes, crustacea, hydroids, bryozoa, and tunicates (Kerrison *et al*. 2016; Kim *et al*. 2017; Stévant *et al*. 2017; Largo *et al*. 2020a). These seaweed-associated organisms may include seaweed pests and invasive aquatic species (Campbell *et al*. 2019b; Largo *et al*. 2020a; Cottier-Cook *et al*. 2021; Bhuyan 2023). Herein we use the term 'seaweed pests' to describe organisms that may be native or non-native and that have a detrimental effect on seaweeds. Invasive aquatic species (IAS) are species that are non-native to an area, and that have wide-ranging negative impacts, including on ecosystems, aquaculture, fisheries and other maritime industries. Seaweed pests relevant to farmed seaweeds are discussed in this section. IAS are discussed in the following section (*Environmental biosecurity risks*), along with environmental biosecurity risks of seaweed diseases and pests.

Several endophytic seaweeds, including the brown *Laminariocolax* and *Laminarionema* spp. (Ectocarpales) and the green *Ulvella* (formerly *Acrochaete*) spp. (Ulvales), are obligate or facultative parasites of seaweeds and infect both wild and cultivated red and brown seaweeds (Ellertsdottir and Peters 1997; Burkhardt and Peters 1998; Ogandaga *et al*. 2017; Bernard *et al*. 2018a; Murua *et al*. 2023). A red seaweed *Vertebrata lanosa* (Ceramiales) is an obligate epiphytic parasite of the brown seaweed *Ascophyllum nodosum* (Longtin and Scrosati 2009). Impacts of parasitic endophytic algae on infected seaweeds include lesions, frond holes, thallus deformations, decreased growth and reduced reproductive output (Colorni 1989; Burkhardt and Peters 1998; del Campo *et al*. 1998; Neill *et al*. 2008; Choi *et al*. 2015; Craigie *et al*. 2019; Murúa *et al*. 2019). Thallus deformations in kelp can also weaken their attachment to culture ropes, leading to significant biomass loss (Neill *et al*. 2008).

Laminariocolax and *Laminarionema* spp. do not appear to be strictly host-specific. In particular, *Laminariocolax aecidioides* has a widespread global distribution and infects a broad range of Laminariales (Bernard *et al*. 2018b). The prevalence of infection by these ectocarpic parasites varies between different co-occurring species in wild seaweeds in some areas, however, suggesting differential susceptibility (Bernard *et al*. 2018a; Bernard *et al*. 2018b). Different seaweeds show varying defensive responses to *Laminarionema* spp. exposure that may drive differences in susceptibility (Xing *et al*. 2021). Patterns in parasite prevalence across seaweeds are, however, not consistent between geographic areas even with the same suite of parasites and host seaweeds present (Bernard *et al*. 2018b). The ectocarpic *Mikrosyphar zosterae* that infects seagrasses has also been recorded in the red seaweed *Chondrus ocellatus* (Ogandaga *et al*. 2016; Ogandaga *et al*. 2017) and in brown seaweeds *Colpomenia* and *Leathesia* sp. (Martins *et al*. 2022), suggesting a broad host range for this parasite. Host specificity in *Ulvella* spp. is not well characterised, but *Ulvella endozoica* is known from both gorgonian corals and several red seaweed species (Soares *et al*. 2021), suggesting low host specificity.

Phytomyxea (kingdom Chromista, phylum Rhizaria) are microscopic obligate endoparasites that infect brown seaweeds and cause galls or other deformities, although infections may occur without clinical disease (Murua *et al*. 2017; Mabey *et al*. 2021). Galls alter the hydrodynamics of the host plant and may promote dislodgement due to increased drag, with long-range dispersal of the parasite possible on drifting blades (Mabey *et al*. 2021). *Maullinia* spp. that infect bull kelp form resting cysts that may facilitate dispersal and re-infection (Murua *et al*. 2017). Phytomyxea may be able to rapidly adapt and infect different host taxa (Neuhauser *et al*. 2014), but infectivity and the mechanisms of pathogenicity are not established for these parasites (Goecke *et al*. 2012).

Figure 6. *Maullinia braseltonii* sp. nov. (Phytomyxea) infection in the bull kelp *Durvillaea antarctica* showing galls (white arrow heads) on a *Durvillaea antarctica* blade. Arrow indicates the area where the frond ruptured. It shows a dense cluster of galls. Scale bar: 12 cm. Reproduced from Murua *et al*. (2017).

A range of red, brown and green seaweeds can occur as epiphytes on seaweed, causing issues for cultivated seaweeds through competition for light and nutrients (Potin 2012; Stévant *et al*. 2017; Largo *et al*. 2020a; Behera *et al*. 2022a; Msuya *et al*. 2022; Murua *et al*. 2023). Epiphytic filamentous algae of the *Polysiphonia-Neosiphonia* group, now identified as *Melanothamnus* spp. (Ceramiales, Figure 7), are considered a serious pest of cultivated jellyweeds (Largo *et al*. 2020a; Ward *et al*. 2021; Msuya *et al*. 2022). Diatoms and cyanobacteria cause issues for nori production by forming a felt-like covering on blades that results in reduced growth and product quality, and sometimes degeneration and loss of affected blades (Kim *et al*. 2014; Bernard 2018). Epiphytic invertebrates (Figure 8), including fouling species such as hydroids, bryozoa and bivalves, and mesograzers such as gastropods and small crustacea, including caprellids, isopods, and amphipods, also commonly occur on seaweeds and can negatively impact their cultivation (Neill *et al*. 2008; Kerrison *et al*. 2016; Kim *et al*. 2017; Stévant *et al*. 2017; Walls *et al*. 2017).

Figure 7. Signs of *Melanothamnus* infection on a *Kappaphycus alvarezii* branch harvested from Kota Belud, Sabah. Reproduced from Sugumaran *et al*. (2022).

Figure 8. Photos of epiphytic organisms on cultured kelp. Hydroid (a), bryozoan (c), polychaete (e), algae (g), and caprellid (i) encrusting blades of *Saccharina japonica*. Magnification of hydroid (b), bryozoan (d), polychaete (f), algae (h) and caprellid (j). Bar: 100 μm (b, h and j) and 1000 μm (d and f). Reproduced from Kim *et al*. (2017).

Fouling species can shade seaweed and so reduce productivity, and can reduce product value due to contamination (Kerrison *et al*. 2016; Stévant *et al*. 2017). Damage by grazers can range from small holes on seaweed blades, which may promote infection, to destruction of kelp stipes with subsequent thallus detachment (Neill *et al*. 2008; Kim *et al*. 2017).

The microscopic and seedling phases of many seaweeds are sensitive to contamination at the hatchery and early nursery stages. Microorganisms, including other algae, fungi, bacteria, cyanobacteria and micro zooplankton, (primarily protozoans) can graze on or outcompete the macroalgal cultures (Redmond *et al*. 2014).

Environmental biosecurity risks of seaweed aquaculture

Aquaculture is a leading vector of IAS introductions, including of non-native farmed seaweeds and co-introductions of pests and disease with farmed species (Naylor *et al*. 2001; Williams and Smith 2007; Campbell *et al*. 2019b; Cottier-Cook *et al*. 2021; Bhuyan 2023). IAS, pests and diseases may be co-introduced on farmed seaweeds, in transport media (e.g., seawater) or with associated infrastructure and vessels (Campbell *et al*. 2019b; DAWE 2020; Cottier-Cook *et al*. 2021; Tonk *et al*. 2021; Bhuyan 2023). In addition to pests of seaweeds, seaweed epiphytes may include IAS that pose environmental biosecurity risks. For example, the invasive bryozoan *Membranipora membranacea* is a common fouling species on many large brown seaweeds (Laminariales and Fucales), including farmed winged kelp and wild bull kelp (Yorke and Metaxas 2012; Walls *et al*. 2017; Avila *et al*. 2020), and invasive filamentous algae also occur on seaweeds (Tiberti *et al*. 2021). Artificial structures associated with aquaculture can harbour pests and diseases, and may lead to re-infection where re-used (Stévant *et al*. 2017; Campbell *et al*. 2019b; Kambey *et al*. 2021c) or act as stepping-stones for the spread of pests or IAS (Campbell *et al*. 2019b; van den Burg *et al*. 2020). Pests and diseases introduced to wild seaweeds can serve as a reservoir for infection of farmed seaweed (SCAAH 2016; Valero *et al*. 2017; Murua *et al*. 2023). The presence of farmed seaweed biomass may also facilitate the spread of, or increase the intensity of, endemic diseases in wild seaweeds (Bhuyan 2023).

IAS can have serious environmental impacts, including altering biodiversity and ecosystem function (Schaffelke and Hewitt 2007; Williams and Smith 2007; Petrocelli and Cecere 2015), and the establishment of invasive species can facilitate additional species introductions (Williams and Grosholz 2008). Once established, IAS are typically ineradicable, and there are limited options for control (Bax *et al*. 2003; Williams and Grosholz 2008; Davidson *et al*. 2015; Petrocelli and Cecere 2015).

Fouling or weedy species with high growth rates and potential for spread may have impacts through overgrowth of, or outcompeting, native species for space or resources, or by damaging or impairing infrastructure function (Ruiz *et al*. 1997; Wallentinus and Nyberg 2007; Tiberti *et al*. 2021). Predatory or herbivorous species, including meso-grazers, can impact native prey and seaweeds, and compete with native species (Williams and Grosholz 2008). Filter-feeding IAS compete with native filter feeders and can have large impacts on primary and secondary productivity, while habitat-forming species may act as ecosystem engineers, with wide-ranging impacts, including on food-web functions (Schaffelke and Hewitt 2007; Williams and Smith 2007; Williams and Grosholz 2008; Petrocelli and Cecere 2015). Economic and social impacts of IAS include reduced productivity or increased costs for fisheries, aquaculture, tourism and infrastructure, and some IAS have socio-economic, human health or amenity value impacts (Bax *et al*. 2003; Schaffelke and Hewitt 2007; Williams and Smith 2007; Petrocelli and Cecere 2015).

Seaweeds that have been introduced either intentionally for aquaculture or unintentionally via other aquaculture or human-mediated pathways are among some of the worst invasive species globally (Schaffelke and Hewitt 2007; Williams and Smith 2007; Petrocelli and Cecere 2015). In several cases, non-native seaweeds introduced for aquaculture have become naturalised, despite not being expected to be able to reproduce in the relevant areas. This includes wakame in France, *Gracillaria* spp. in Hawai'i, nori (*Pyropia* spp.) in the United States, and jellyweeds (*Kappaphycus* and *Eucheuma* spp.) in parts of the Pacific, Africa, Asia and the Caribbean (Naylor *et al*. 2001; Ask *et al*. 2003; Pickering *et al*. 2007; Kim *et al*. 2019).

Wakame (Figure 9) has also formed invasive populations in southern Australia (Victoria, Tasmania and South Australia) and New Zealand after being accidentally introduced (Sanderson 1990; Campbell and Burridge 1998; Forrest and Blakemore 2006; Primo *et al*. 2010; PIRSA 2024). Other seaweeds with aquaculture potential are also invasive or potentially invasive. *Asparagopsis* spp. have formed invasive populations in the Mediterranean and South Africa (Andreakis *et al*. 2004; Zanolla *et al*. 2018; Zanolla *et al*. 2022), while the genus *Caulerpa*, which includes edible species farmed as sea grapes, includes several invasive species, the best-known being *C. taxifolia*, which has formed invasive populations in the Mediterranean and south-eastern Australia (Manning and Deveney 2008; Figure 10). Other invasive *Caulerpa* spp. include *C. cylindracea* in the Mediterranean and southern Australia, *C. brachypus* in the United States, *C. webbiana* in the Azores, and C. *chemnitzia* in the Galapagos (Schaffelke *et al*. 2006; Amat *et al*. 2008; Lapointe and Bedford 2010; Zubia *et al*. 2019; Keith *et al*. 2022).

Invasive seaweeds include epiphytic and endophytic species that can severely impact their host species, both wild and farmed (del Campo *et al*. 1998; Longtin and Scrosati 2009; Potin 2012; Davidson *et al*. 2015; Kim *et al*. 2017; Ogandaga *et al*. 2017). Impacts of other invasive seaweeds are typically driven by their ability to out-compete native species for space or resources, leading to reduced biodiversity and depleted ecosystem services (Schaffelke and Hewitt 2007; Williams and Smith 2007; Davidson *et al*. 2015). Invasive seaweeds may provide a poorer-quality habitat or feed source than displaced native species, and may alter local hydrodynamics, nutrient cycling and sediment characteristics, with flow-on negative biological effects (Williams and Smith 2007; Fernandes *et al*. 2009; Gribben *et al*. 2009; Davidson *et al*. 2015).

Cultivation of native seaweeds is recommended globally to avoid the introduction of invasive seaweed species, and the import of non-native seaweeds to develop an Australian seaweed industry is unlikely to be allowed. Farmed native strains can, however, also pose risks to wild populations (Campbell *et al*. 2019b; Nepper-Davidsen *et al*. 2021; Murua *et al*. 2023). Farmed seaweeds may comprise strains selected for rapid growth, which have the potential to outcompete and displace wild strains (Stévant *et al*. 2017; Campbell *et al*. 2019b; Kambey *et al*. 2020; Murua *et al*. 2023). Escapes of farmed genotypes to wild populations may be difficult to detect (Brakel *et al*. 2021).

Cryptic invasions may occur where translocated genotypes out-compete naturally occurring genotypes in an area (Brakel *et al*. 2021; Murua *et al*. 2023). For example, genotypes of the jellyweed *Eucheuma denticulatum* introduced for farming in Tanzania now dominate wild seaweed beds, even away from aquaculture regions, and wild populations show decreased genetic diversity since the advent of farming due to the dominance of the introduced genotype (Tano *et al*. 2015).

Farmed strains often have low genetic diversity and pose a risk to wild stocks through farmed-to-wild gene flow via release of propagules or reproductive material, with subsequent impacts on the genetic structure and diversity of wild seaweeds (Barbier *et al*. 2020; Kambey *et al*. 2020; Cottier-Cook *et al*. 2021; Bhuyan 2023). Even where farmed material is genetically diverse, genetic impacts may occur through mixing strains from different biogeographic regions, with the consequences of interbreeding being difficult to predict (Stévant *et al*. 2017; Yarish *et al*. 2017). Haplo-diploid species, such as most seaweeds, are less susceptible to inbreeding depression than diploids, but are at greater risk of outbreeding depression (Weeks *et al*. 2011).

The risk of genetic impacts from seaweed aquaculture will generally be greatest where seaweeds, or viable genetic material, are translocated to, or released in, areas with genetically distinct populations of the same species (DAWE 2020) or that contain a closely related species with which hybridisation is possible (Campbell *et al*. 2019b; Cottier-Cook *et al*. 2021). The risk is particularly high where the wild stock carries rare or important genotypes that may be lost through inter-breeding (Campbell *et al*. 2019b; DAWE 2020; Cottier-Cook *et al*. 2021).

Hybridisation may occur between related seaweeds, particularly in Laminariales (Kusumo and Druehl 2000; Akita *et al*. 2021). Within this order, crosses between species belonging to different families may sometimes occur (Liptack and Druehl 2000). Within the Fucales, congeneric species may hybridize (Coyer *et al*. 2007; Hodge *et al*. 2010). Hybridisation between red seaweeds is relatively rare, but has been recorded in Gelidiales (Boo *et al*. 2019).

Figure 9. Wakame (*Undaria pinnatifida*). Photograph: CSIRO, CC BY 3.0 via Wikimedia Commons.

Figure 10. Invasive *Caulerpa taxifolia* in the Port River – Barker Inlet system, Adelaide. Photograph: Kathryn Wiltshire, SARDI Aquatic and Livestock Sciences.

Approaches to address seaweed industry biosecurity risks

Despite widespread recognition of the importance of biosecurity for seaweed industry development, existing biosecurity policies, guidelines and management frameworks are lacking (Cottier-Cook *et al*. 2016; Msuya *et al*. 2022; Spillias *et al*. 2022; Murua *et al*. 2023).

Seaweeds are not explicitly included in the biosecurity policies of many jurisdictions, or are included only in policies and guidelines that are not legally binding (Mateo *et al*. 2020; Rusekwa *et al*. 2020; Kambey *et al*. 2021b; Mateo *et al*. 2021; Campbell *et al*. 2022; Murua *et al*. 2023). The Food and Agriculture Organization of the United Nations (FAO) has developed a progressive management plan for aquaculture biosecurity (PMP/AB) that is being adapted for seaweeds, but seaweed-producing countries need to adopt their own PMP/AB based on the species being cultivated, relevant pests and diseases, and practices associated with their cultivation (Cottier-Cook *et al*. 2022). The World Trade Organization (WTO), through the International Plant Protection Convention, has included standards for seaweeds in the International Sanitary and Phytosanitary Measures (ISPMs) since 2014 (IPCC 2017). Appropriate regional frameworks are, however, essential to ensure appropriate implementation of the ISPMs (Campbell *et al*. 2019a).

General guidance on disease management, diagnostics, surveillance, disinfection and quarantine for aquaculture operations are provided in Australia, but these leave implementation to producers, with local regulators determining requirements (Palić *et al*. 2015), which consequently vary between jurisdictions (SCAAH 2016). Existing Australian policies and guidelines for aquatic biosecurity (SCAAH 2016; DAWE 2020; Bradley 2023) do not explicitly include seaweeds, although much of the information is relevant to seaweed aquaculture.

Biosecurity processes need to be practical and economically favourable, be based on scientifically supported procedures, and effectively address key risks (Palić *et al*. 2015; Cottier-Cook *et al*. 2022). The limited resources available to seaweed farmers in many global regions restricts their application of biosecurity practices (Kambey *et al*. 2021b; Mateo *et al*. 2021; Campbell *et al*. 2022). Biosecurity management in seaweed aquaculture is also hampered by a general lack of information, including poor understanding of causative agents and pathways for disease, limited research on disease prevention or treatment, lack of clear genetic identity of cultivated seaweed varieties and limited knowledge of the genetic structure of wild populations (Campbell *et al*. 2019a; Ward *et al*. 2019; Campbell *et al*. 2022; Murua *et al*. 2023).

Key components of developing effective biosecurity processes include identification, risk assessment and prioritisation of important pests and diseases; determining critical control points for disease or pest entry and exit; carrying out regular surveillance and diagnostic sampling; and accurate record keeping and auditing (Palić *et al*. 2015; SCAAH 2016; Campbell *et al*. 2022; Cottier-Cook *et al*. 2022; FAO 2022; Bhuyan 2023). Pests and diseases can be introduced via brood stock, seed stock, reproductive material (e.g., eggs/spores), material harvested or introduced from other sites, wild stocks, and inanimate objects, such as equipment and vessels (Palić *et al*. 2015; SCAAH 2016; DAWE 2020; Cottier-Cook *et al*. 2022). All stages in the production process should be critically examined to determine potential points for disease and pest entry or escape (Palić *et al*. 2015; SCAAH 2016; Bhuyan 2023). Standard approaches for preventing disease and pest entry include health checks, quarantine, cleaning and disinfection (Palić *et al*. 2015; SCAAH 2016; Mantri *et al*. 2022).

Surveillance programs for pests and diseases need to be supported by available seaweed health services, reporting systems, notification systems and record keeping (Campbell *et al*. 2019b; Cottier-Cook *et al*. 2022; Mantri *et al*. 2022). Contingency plans for a response should a disease occur are critical (Palić *et al*. 2015; SCAAH 2016; Mantri *et al*. 2022). It is important that suitable legal powers are in place, and that adequate resources and diagnostic facilities are available (Palić *et al*. 2015). Procedures and facilities for decontamination and for potentially destroying and disposing large volumes of diseased stock are also required (SCAAH 2016). Protocols for early detection and capacity for diagnosis of seaweed diseases need to be further developed (Mateo *et al*. 2020; Cottier-Cook *et al*. 2022). Molecular methods, including environmental DNA, may be useful for monitoring pests and diseases (Tonk *et al*. 2021). Multiple lines of investigation, including molecular techniques and histology, should be applied in combination for disease investigation (Ward *et al*. 2021).

Considerations for biosecurity planning

Cultivation systems and farmed species

Applicable biosecurity strategies for seaweed aquaculture will depend on the cultivation system used. Aquaculture facilities in general fall in to one of four categories: open systems, where there is little to no control over movements of either stock or water (e.g., ranching); semi-open systems (e.g. at-sea aquaculture using longlines), where there is some control over movements of stock and equipment but not water; semi-closed systems (e.g. flow-through pond and tank systems), where there is a high level of control over stock movements and some control over water movement; and closed systems (e.g. recirculating aquaculture systems), where there is a high level of control over movements of stock, equipment and water (Georgiades *et al*. 2016; DAWE 2020). Most seaweed aquaculture globally is carried out in either semi-open or semi-closed systems, although closed systems are used in some cases. Open systems would not typically be used for farming seaweeds, but the out-planting of seaweeds for restoration or restocking would effectively be an open system.

The main systems used for seaweed aquaculture vary depending on the seaweed species, with species biology, particularly the method of reproduction, a key factor in determining the cultivation method and stages (McHugh 2003; Valero *et al*. 2017). Seaweeds comprise a wide range of taxonomic groups with varying, and often complex, life histories. Some key types of seaweeds farmed globally or for which aquaculture is developing in Australia are described below.

Large brown seaweeds

Large brown seaweeds that are cultivated globally include Laminariales, particularly kombu (*Laminaria* and *Saccharina* spp.) and wakame (*Undaria pinnatifida*), and, to a lesser extent, Fucales, such as bull kelps (*Durvillaea* spp.) and hijiki (*Sargassum fusiforme*). Large brown seaweeds are farmed primarily for food and alginate (McHugh 2003; Behera *et al*. 2022a). Laminariales have a two-stage life cycle, with a microscopic gametophyte stage and macroscopic sporophyte stage (Flavin *et al*. 2013; Valero *et al*. 2017), while Fucales produce gametes within specialised reproductive structures, with gametes fusing to form zygotes that develop directly into the next generation of adults (Hwang *et al*. 2006; Pang *et al*. 2008; Largo *et al*. 2020b). Neither Laminariales nor Fucales regrow from cuttings.

Cultivation of large brown seaweeds typically involves a hatchery and/or nursery stage where spores or gametes are seeded onto lines and grow to small juveniles (Flavin *et al*. 2013; Valero *et al*. 2017; Largo *et al*. 2020b; Figure 11), followed by out-planting at sea until harvest (Kim *et al*. 2019; Behera *et al*. 2022b). For Laminariales, gametophytes may be vegetatively cultured to increase the quality and quantity available for seeding, to allow out-planting in seasons outside normal reproductive periods, or to allow crossing of selected strains (Flavin *et al*. 2013; Valero *et al*. 2017).

Laminaria, *Saccharina* and *Undaria* spp. do not naturally occur in Australia, although wakame was unintentionally introduced and has established populations in south-eastern Australia (Sanderson 1990; Schaffelke *et al*. 2005; Primo *et al*. 2010). Australia has several native Laminariales, including golden kelp (*Ecklonia radiata*) and giant kelp (*Macrocystis pyrifera*), that are of interest for cultivation (Lorbeer *et al*. 2013; Wiltshire *et al*. 2015). Australia also has a high diversity of native Fucales, including *Durvillaea*, *Sargassum* and *Cystophora* spp., with potential for cultivation (Lorbeer *et al*. 2013; Wiltshire *et al*. 2015).

Figure 11. Golden kelp seeded onto string during nursery cultivation (left) and seedlings for out-planting (right). Photographs: Sasi Nayar, SARDI Aquatic and Livestock Sciences.

Red seaweeds

Hydrocolloid producers

Several red seaweeds are grown predominantly for the hydrocolloids, carrageenan and agar (Bixler and Porse 2011). Farmed carrageenan-producing seaweeds include members of the order Gigartinales: jellyweeds (*Betaphycus*, *Eucheuma* and *Kappaphycus* spp.) and Irish moss (*Chondrus crispus*) (McHugh 2003; Bixler and Porse 2011). Farmed agar producers come from the order Gracilariales, including *Agarophyton*, *Gracilaria* and *Gracilariopsis* spp. Seaweeds of the red order Gelidiales also produce agar (McHugh 2003; Bixler and Porse 2011). These include the agarweeds (*Gelidium* and *Pterocladia* spp.), which are commercially harvested, but for which aquaculture is not yet applied except at a research scale (Buschmann *et al*. 2017).

All the hydrocolloid-producing red seaweeds can be grown from cuttings, with this being the main method used by farms for seed stock production (McHugh 2003; Bixler and Porse 2011; Buschmann *et al*. 2017). Reproduction from spores or tissue culture is also possible and is applied in some cases (Alveal *et al*. 1997; Ask and Azanza 2002; Baweja *et al*. 2009; Bhushan *et al*. 2023). Gigartinales and Gracilariales have alternating diploid (tetrasporophyte) and haploid (gametophyte) generations identical in appearance aside from their reproductive structures (Womersley 1994, 1996). Tetrasporophytes produce tetraspores that grow into gametophytes, while fertile gametophytes develop microscopic carposporophytes that produce carpospores, which develop into the next generation of sporophytes (Womersley 1994, 1996).

Jellyweeds and Gracilariales are grown either at sea or in land-based ponds, tanks or raceways (Ask and Azanza 2002; McHugh 2003; Mantri *et al*. 2022; Sugumaran *et al*. 2022), while Irish moss is grown mainly in land-based systems, but occasionally at sea (Craigie *et al*. 2019). Cuttings taken from one production cycle are normally used as seed stock for the subsequent cycle without separate hatchery or nursery cultivation (Valero *et al*. 2017; Suyo *et al*. 2021). Hatchery cultivation is, however, used for production from spores or tissue culture (Jiksing *et al*. 2022).

Jellyweeds and Irish moss do not occur in Australia, but Australia has a high diversity of native Gigartinales, including from the same family (Solieriaceae) as the commercially farmed jellyweeds (Womersley 1994; Lorbeer *et al*. 2013; Wiltshire *et al*. 2015). Several Gracilariales and agarweeds are also native to Australia (Womersley 1994, 1996; Lorbeer *et al*. 2013; Wiltshire *et al*. 2015).

Nori

Nori *(Porphyra* and *Pyropia* spp., order Bangiales) are red seaweeds grown predominantly for food (McHugh 2003; Buschmann *et al*. 2017). Nori species have a three-stage life cycle with a microscopic shell-boring tetrasporophyte, known as the conchocelis, a macroscopic gametophyte, and a microscopic carposporophyte that grows on the gametophyte (Womersley 1994; Jiksing *et al*. 2022). Cultivation includes hatchery cultivation of the conchocelis stage, which is seeded onto shells and grown in tanks, ponds or raceways, followed by seeding of the gametophyte onto nets for out-planting at sea (Valero *et al*. 2017; Jiksing *et al*. 2022). Several *Pyropia* spp. are native to Australia (Womersley 1994), although not the specific species cultivated elsewhere.

Asparagopsis and other species

Asparagopsis, two species of which are native to Australia and are the focus of several Australian seaweed farming enterprises, belong to the red seaweed order Bonnemaisoniales (Womersley 1996). Seaweeds of this order have a three-stage life history similar to that of nori, i.e., a small free-living tetrasporophyte, a macroscopic gametophyte stage, and a microscopic carposporophyte stage that develops attached to the gametophyte (Womersley 1996). Unlike nori, however, the tetrasporophyte stage of *Asparagopsis* spp. is filamentous and does not require a specific substrate for cultivation (Zanolla *et al*. 2022). Cultivation systems for *Asparagopsis* spp. are in development, but are likely to include hatchery cultivation and grow-out, either at sea or in ponds, tanks or raceways (Kraan and Barrington 2005; Mickelson 2013).

Small-scale cultivation of other red seaweeds occurs globally, including of *Palmaria* spp. (order Palmariales) which are grown for food. *Palmaria* spp. are primarily vegetatively propagated and grown in tanks or ponds (McHugh 2003; Kerrison *et al*. 2016). In addition to *Asparagopsis* spp., many other red seaweeds native to Australia are of potential interest for cultivation for bioproducts or as food, among other potential uses (Kirkendale *et al*. 2010; Lee 2010; Winberg *et al*. 2011; Lorbeer *et al*. 2013; Wiltshire *et al*. 2015).

Green seaweeds

Cultivated green seaweeds include sea lettuces (*Ulva* spp., order Ulvales) and sea grapes (*Caulerpa* spp., order Bryopsidales), which are grown primarily for food or use in animal feeds (Buschmann *et al*. 2017). Green seaweeds have either a single or a two-stage life history, but asexual reproduction is prevalent (Womersley 1984). Ulvales have alternating isomorphic haploid (gametophyte) and diploid (sporophyte) generations, and can reproduce clonally through regeneration from fragments or the development of unmated gametes into gametophytes (Wichard *et al*. 2015; Zhao *et al*. 2023). Bryopsidales display a similar life history to Fucales, with diploid sporophytes producing gametes, which fuse to form zygotes that develop into the next generation of diploid thalli (Clifton and Clifton 1999; Cremen *et al*. 2019). In contrast to Fucales, however, asexual reproduction via fragmentation is the primary means of reproduction in Bryopsidales, with sexual reproduction a relatively rare event (Clifton and Clifton 1999). Bryopsidales also do not have distinct reproductive structures, rather delimited zones of the thallus or sometimes the entire thallus becomes reproductive, with reproductive tissue disintegrating following gamete release (Clifton and Clifton 1999; Cremen *et al*. 2019).

In cultivation, green seaweeds are typically vegetatively propagated, and are normally grown in tanks or ponds due to their relatively delicate structure, although at-sea cultivation has been trialled in some areas (Tanduyan *et al*. 2013; Kerrison *et al*. 2016; Behera *et al*. 2022b).

Several *Ulva* and *Caulerpa* spp. are native to Australia, with southern Australia having a high diversity of *Caulerpa* spp. (Womersley 1984; Lorbeer *et al*. 2013; Belton *et al*. 2019).

Biosecurity strategies for different cultivation systems

At-sea cultivation (open and semi-open systems)

For cultivation at sea, site selection is paramount to ensure suitable abiotic conditions and to avoid areas with a high risk of grazers, epiphytes or disease (Yarish *et al*. 2017; Ward *et al*. 2019; Ndawala *et al*. 2021; Suyo *et al*. 2021). Sensitive areas with a risk of impacts from seaweed aquaculture should also be avoided (Campbell *et al*. 2019b). The risk of environmental biosecurity impacts can be informed by the type and volume of seaweed to be cultivated, the frequency with which new stock will be added, and the nature of the receiving environment, including endemic disease or pest prevalence (DAWE 2020). Understanding pest and disease prevalence in the area where seaweeds are to be cultivated is needed to inform risks to both the cultivated crop and the environment (Jones and Stephens 2006). Farm layout should aim to minimise risks of cross-contamination, with consideration given to water movement patterns (SCAAH 2016; Mateo *et al*. 2020). Crops from different cultivation cycles should be separated to prevent cross-infection (Kambey *et al*. 2021a). Establishing sites to separate life history stages, year classes and batches of seaweeds typically increases costs but improves resilience to disease events (Kambey *et al*. 2021a; Campbell *et al*. 2022).

The timing of out-planting and harvest is important to minimise risks of epiphytes and environmentally mediated disease (Stévant *et al*. 2017; Tonk *et al*. 2021; Biancacci *et al*. 2022; Chowdhury *et al*. 2022; Mantri *et al*. 2022). Epiphyte occurrence is typically seasonal, with algal epiphytes in particular proliferating in summer due to warmer water and greater light intensity (Kim *et al*. 2017; Largo *et al*. 2020a). Understanding the biology and seasonality of important epiphytes can assist in managing these pests (Aroca *et al*. 2020). Cultivation method and stocking density also influence pest and disease risk. Stocking seaweed at a sufficient density can assist in preventing epiphytes, but the risk of disease transmission increases at higher stocking densities (Wang *et al*. 2014; Ward *et al*. 2021; Sugumaran *et al*. 2022). Cultivation method affects disease incidence, but the most suitable method will vary depending on the species cultivated and the location (Suyo *et al*. 2021; Sugumaran *et al*. 2022).

Options for controlling pests and diseases in open and semi-open systems are limited (DAWE 2020; Mateo *et al*. 2020; Murua *et al*. 2023). This is particularly true for extractive species, such as seaweed, because therapeutic agents cannot be delivered in feed, which is an option for supplementary fed aquaculture species, such as fish (Kambey *et al*. 2020). Difficulty in accessing farms, e.g., where they are located further offshore, can further limit management options (Campbell *et al*. 2022). Entry-level biosecurity is therefore key for these cultivation systems.

The use of healthy seed stock is important (Kraan 2020; Kambey *et al*. 2021a; Ndawala *et al*. 2021; Behera *et al*. 2022a; Cottier-Cook *et al*. 2022). For the clonally propagated seaweeds, material selected from each cultivation cycle is often used as seed stock for the next cycle, allowing the propagation of desirable phenotypes (e.g., faster growing, higher survival) (Valero *et al*. 2017; Suyo *et al*. 2021). The reuse of cultivated material is also common in many regions due to the relatively higher cost of purchasing new seed stock (Suyo *et al*. 2021). The reuse of cuttings as seed stock can, however, contribute to disease transmission (Cottier-Cook *et al*. 2021; Kambey *et al*. 2021c; Ndawala *et al*. 2022). The introduction of seed stock of new species or strains can improve crop vigour, but translocation of seaweed may facilitate the introduction of pests and diseases (Kambey *et al*. 2020; Brakel *et al*. 2021; Mateo *et al*. 2021). Seeding material should be inspected prior to out-planting for signs of pests and disease, such as discolouration, wounds and the presence of epiphytes (FAO 2022). Although apparently healthy cuttings are selected as seed stock, where this is based only on visual inspection, some biosecurity threats, e.g., microscopic endophytes, may not be detected (Kambey *et al*. 2021c).

Many seaweed diseases are associated with opportunistic pathogens, so it is also important to avoid stress during out-planting of seedlings, e.g., by avoiding desiccation (Mateo *et al*. 2021). Dipping seedlings in nitrogen-rich media or a biostimulant, or pre-treating with antimicrobials, prior to out-planting can improve their performance and disease resistance (Tahiluddin and Terzi 2021; Jiksing *et al*. 2022; Sugumaran *et al*. 2022). Appropriate fertilisation during growth can also assist in preventing disease (Ndawala *et al*. 2021), but excessive fertiliser use or environmental eutrophication can promote epiphytes and some diseases (Largo *et al*. 2020a; Faisan *et al*. 2021; Mantri *et al*. 2022). The potential environmental impacts of residual chemicals or added nutrients must be considered, and these practices are not always legal or acceptable (Campbell *et al*. 2019b; Mateo *et al*. 2021; Mantri *et al*. 2022).

Washing and mild chemical treatments may be effective to remove or inactivate some pests and diseases, but are unlikely to prevent all problems, particularly endophytes (Pickering *et al*. 2007). There is also a risk of introducing pests and disease in transport media (e.g., seawater). Transport media should therefore be appropriately treated and disposed of, or water from the destination area used for transport (DAWE 2020). Quarantine procedures can help prevent pest and disease introductions, but the effectiveness of quarantine protocols for seaweeds needs to be assessed (Pickering *et al*. 2007; Kambey *et al*. 2021a; Mantri *et al*. 2022). Appropriate biosecurity regulations are important to ensure that quarantine measures are routinely applied (Msuya *et al*. 2022). Nursery production, whether of vegetatively propagated or sexually reproducing seaweeds, can assist in the provision of healthy seed stock, contingent on suitable biosecurity practices for these production systems as detailed below. Regardless of the source of seed stock, record keeping and traceability are important to manage biosecurity risks (Kambey *et al*. 2021a; Cottier-Cook *et al*. 2022).

Options to minimise the risk of farm-to-wild gene flow, or of farmed seaweed strains becoming pests, include using native species; specifically, genetically diverse cultivars that are grown within their natural area of occurrence (Yarish *et al*. 2017; Kim *et al*. 2019; Barbier *et al*. 2020; Cottier-Cook *et al*. 2021; Nepper-Davidsen *et al*. 2021); using non-fertile cultivars or a single sex of a dioecious species for grow-out (Loureiro *et al*. 2015; Campbell *et al*. 2019b; DAWE 2020; Brakel *et al*. 2021; Bhuyan 2023); or cultivating seaweeds under abiotic conditions suitable for growth but not reproduction. The last strategy carries greater risk, however, because suitable conditions for reproduction are not always well known or may change with domestication. Knowledge of genetic structure in wild stocks is important to inform genetic risks and to assist breeding programs in maintaining genetic diversity (Loureiro *et al*. 2015; Campbell *et al*. 2019b; Barbier *et al*. 2020; Brakel *et al*. 2021; Nepper-Davidsen *et al*. 2021). Ploidy control is also a possible strategy for controlling stock fertility (Brakel *et al*. 2021).

There is the potential for farm infrastructure and equipment, including vessels, to host or introduce IAS, pests and diseases (Palić *et al*. 2015; Stévant *et al*. 2017; Campbell *et al*. 2019b; Kambey *et al*. 2021c). New cultivation equipment (e.g., lines, buoys) should be used if possible, or equipment cleaned and decontaminated between crop cycles (FAO 2022). Sharing equipment between farms should be avoided or suitable disinfection applied (Mateo *et al*. 2021). Sun-drying is employed for disinfection in jellyweed cultivation (Kambey *et al*. 2021a; Mateo *et al*. 2021), while freeze-storage of nets used for nori cultivation can assist in reducing the spread of bacterial infections and some water moulds, but does not prevent infection entirely (Klochkova *et al*. 2011; Sugumaran *et al*. 2022). Small vessels can be washed with freshwater and allowed to sun-dry between uses (Kambey *et al*. 2021a). Larger vessels are, however, employed for some farms and activities, particularly for longline installation and mechanised harvesting (Tonk *et al*. 2021), and are more difficult to clean and decontaminate. Appropriate application and maintenance of anti-fouling on vessels and infrastructure can assist in preventing the spread of pests and diseases by these vectors (Georgiades *et al*. 2016). Vessel type and the frequency of activities will vary depending on the farming system and location, with consideration of these factors important in managing vessel-related risks (Tonk *et al*. 2021).

Regular surveillance and farm maintenance can assist in managing and preventing pest and disease outbreaks (Palić *et al*. 2015; Suyo *et al*. 2021; Cottier-Cook *et al*. 2022; FAO 2022). Maintenance practices employed in many areas, are, however, labour intensive (Kambey *et al*. 2021c; Behera *et al*. 2022a). These practices include removing epiphytes by hand, removing any unhealthy tissue, shaking lines to dislodge loose epiphytes and detritus, and regularly cleaning seaweed and lines, e.g., by wiping with a soft cloth (Ask and Azanza 2002; Yarish *et al*. 2017; Kambey *et al*. 2021a; Kambey *et al*. 2021c; Mateo *et al*. 2021; Ndawala *et al*. 2022). Appropriate (e.g., to landfill) disposal of removed material, particularly potentially diseased tissue, is important to prevent reinfection (Yarish *et al*. 2017; Kambey *et al*. 2021a; Kambey *et al*. 2021c). Where disease or epiphytes are progressing, removal or early harvest of the entire crop cycle may be required (Loureiro *et al*. 2015; Kim *et al*. 2017; Yarish *et al*. 2017; Suyo *et al*. 2021).

Post harvest, any material with signs of potential disease, such as bleaching or decay, should be removed or destroyed to avoid infecting the next crop (Behera *et al*. 2022a). Harvested material should be quarantined from new stock, and crop cycles separated to prevent cross-infection (Kambey *et al*. 2021a; Behera *et al*. 2022a). Fallowing or moving farming locations between crop cycles can also assist in re-introducing pests or disease (Brakel *et al*. 2021; Behera *et al*. 2022a). Crop rotation using different species may also be effective (Behera *et al*. 2022a; Ndawala *et al*. 2022).

Polyculture, including co-cultivation of multiple seaweed species or cultivation of seaweeds as the extractive component in integrated multi-tropic aquaculture (IMTA) systems, can benefit seaweed crop health (Tahiluddin and Terzi 2021; Ndawala *et al*. 2022). Metabolites produced by several seaweeds can deter potentially pathogenic bacteria and have a probiotic effect on potentially protective strains of bacteria (Saha *et al*. 2019). The co-cultivation of seaweeds that produce anti-microbials with other seaweeds may assist in preventing disease (Tahiluddin and Terzi 2021), and growing seaweed with fed species, e.g., fish, can assist crop health by providing seaweed with sufficient nutrients while avoiding environmental eutrophication (Cottier-Cook *et al*. 2016; Cottier-Cook *et al*. 2021). Microbiome interactions between co-cultivated crops are not easy to predict, however, and may sometimes be detrimental, e.g., co-cultivation of *Ulva* spp. with oysters increased oyster susceptibility to ostreid herpesvirus infection, while brown (*Fucus*) and red (*Solieria*) seaweeds did not impact oyster health (Dugeny *et al*. 2022). The co-cultivation of *Ulva* spp. (or other seaweeds *Gracilaria* and *Dictyota*) with shrimp, in contrast, positively affects shrimp health and disease resistance (Anaya-Rosas *et al*. 2019). The benefits of polyculture systems also need to be weighed against the risks associated with having multiple sources of cultivated stock.

Closed and semi-closed systems

Seaweed cultivation systems that are typically semi-closed include flow-through ponds and tanks, while hatcheries and nurseries may be closed or semi-closed. These systems provide varying levels of control over entry and exit points for pests and diseases, but more control than semi-open systems (e.g., at-sea cultivation). Different areas within hatchery and nursery systems may have different health status, and so it is important to consider within-farm biosecurity as well as entry and exit points for pests and diseases (SCAAH 2016). Movements within a farm should be from areas with the highest health status to those with potentially lower status, with the use of dedicated equipment specific to each area and appropriate cleaning and decontamination procedures applied (SCAAH 2016). It is important to consider farm layout, including the locations of access points for staff and visitors, water intake, supply and discharge points, the locations of production and quarantine areas, typical stock movement patterns, and the locations of waste disposal, equipment storage and cleaning areas (SCAAH 2016). Farm layout should consider the potential for water sprays or aerosols to spread disease (SCAAH 2016).

The health of incoming material, e.g., brood stock or seed stock, is important (Flavin *et al*. 2013; SCAAH 2016; Yarish *et al*. 2017). Material should be quarantined where there is doubt about its health status (SCAAH 2016; Kambey *et al*. 2021a). A suggested quarantine procedure for seaweeds (Kambey *et al*. 2021a) is to maintain material in tanks using ultraviolet-sterilised, filtered seawater for a 10-to-14-day period, with water exchanged approximately every three days. Tanks should be disinfected, e.g., chlorine-treated, prior to the introduction of quarantined material and at each water exchange, with material ideally transferred to a new, disinfected tank. Water from quarantine tanks should be chlorine-treated or otherwise disinfected prior to disposal. Quarantined material should be cleaned with filtered seawater prior to being introduced and regularly inspected under magnification through the quarantine period. Molecular tests to detect pests or disease should be applied if available. Further investigation, is, however, needed to assess the efficacy of quarantine procedures for seaweed (Pickering *et al*. 2007; Kambey *et al*. 2021a; Mantri *et al*. 2022).

Fertile material used for hatchery spore production or micropropagation should be selected to be as clean and healthy as possible (Flavin *et al*. 2013; Wang *et al*. 2014; Yarish *et al*. 2017). Procedures for decontaminating brood stock material include excising clean, fertile sections or apices; rinsing in sterile seawater; and wiping with paper towel, a clean, soft cloth or sterile cotton swabs (Flavin *et al*. 2013; Redmond *et al*. 2014; Yarish *et al*. 2017). Kelp tissue can also be carefully scraped with a razor blade to remove epiphytes, and additionally treated with dilute iodine (e.g., povidone-iodine) (Flavin *et al*. 2013; Redmond *et al*. 2014; Yarish *et al*. 2017), while epiphytes can be removed from red seaweed apices by dragging through agar on petri dishes (Redmond *et al*. 2014). Tissue used for spore production or micropropagation should be processed away from the nursery area to prevent cross-contamination, and appropriate equipment (e.g., disposable gloves) should be used during preparation (Flavin *et al*. 2013). Bleach, mild detergents (e.g., dish soap) and isopropyl alcohol can be used to disinfect equipment and benchtops (Flavin *et al*. 2013). Kelp spores can be examined under a microscope to ascertain typical healthy behaviour, being straight-line movement (Flavin *et al*. 2013).

Autoclaved natural seawater is recommended for spore collection and when preparing axenic tips for micropropagation, and filtered, sterilised natural seawater is recommended for early nursery cultivation (Flavin *et al*. 2013; Redmond *et al*. 2014; Wang *et al*. 2014; Yarish *et al*. 2017). Autoclaving is ideal for sterilisation but only practical for relatively small volumes, while ultraviolet sterilisation can be applied to larger water volumes (Flavin *et al*. 2013; Redmond *et al*. 2014). Before ultraviolet sterilisation, water should be filtered to 0.2 µm using stages from coarse to fine filtration (Flavin *et al*. 2013; Redmond *et al*. 2014). Monitoring, e.g., by screening for common non-pathogenic microorganisms, to ensure effective sterilisation is important (SCAAH 2016). Water should be stored in dark, insulated tanks, and repeated filtration and sterilisation applied prior to use where warranted (Flavin *et al*. 2013). Nursery tanks can be fitted with individual ultraviolet sterilisers, and chlorine dioxide can be used to disinfect filtration equipment after use (Flavin *et al*. 2013). Artificial seawater can be used but natural seawater typically produces better results (Flavin *et al*. 2013; Redmond *et al*. 2014). Where seawater is pumped into a facility, the intakes and outfalls should be positioned to avoid cross-contamination (SCAAH 2016).

Diatoms can be a serious pest during the microscopic life stages, particularly for kelp gametophytes (Redmond *et al*. 2014). The addition of low-dose germanium dioxide can assist in preventing diatom growth (Redmond *et al*. 2014). Manipulation of the pH level and salinity at the nursery stages can assist in minimising epiphyte contamination (Behera *et al*. 2022a; Mantri *et al*. 2022), and calcium hypochlorite, potassium permanganate or antimicrobials (e.g., erythromycin) can be applied to prevent growth of at least some pathogens (Wang *et al*. 2014; Cottier-Cook *et al*. 2022). Disinfectants are preferred to antimicrobials for disease prevention because overuse of antimicrobials contributes to the growing problem of antimicrobial resistance (Santos and Ramos 2018). It should also be noted that several seaweed-associated microbes positively influence seaweed health, and the indiscriminate use of antimicrobials poses a risk of reducing or removing protective microbes, leading to increased risk of some diseases (Weinberger *et al*. 1997; Egan *et al*. 2014; Li *et al*. 2022).

Suitable abiotic conditions should be maintained, the health of cultivated stock should be regularly monitored, and records should be kept on health status, water quality, disease testing results and any treatments applied (Flavin *et al*. 2013; Redmond *et al*. 2014; Palić *et al*. 2015; SCAAH 2016). Record keeping should also include the origin of stock; movements of stock onto, within or from the farm; and staff and visitor movements (SCAAH 2016). All wastes from the facility should be contained and properly disposed of (SCAAH 2016).

Contingency plans for a response should a disease occur are critical (Palić *et al*. 2015). Clear triggers for identifying disease emergencies and protocols to be implemented in the case of an outbreak are needed (SCAAH 2016; Bradley 2023). These protocols may include securing areas and ceasing activities and stock movements (SCAAH 2016), and containing effluent where possible (Palić *et al*. 2015). Semi-closed systems may be able to be contained, but possible impacts on water quality within the cultivation system need to be considered (DAWE 2020). Contingency planning might include back-up power and sterilisation facilities, bunding, and pond or tank design to facilitate containment, and should include procedures for destroying and disposing diseased stock (SCAAH 2016; DAWE 2020). Clear procedures for diagnostic sample collection and reporting should also be established (SCAAH 2016; DAWE 2020; Bradley 2023).

Strategies to treat infection and improve seaweed health

Control and treatment options for seaweed diseases are scarce, and diagnostic methods need further development (Ward *et al*. 2019; Strittmatter *et al*. 2022). Globally, chemical treatments have been trialled in some cases but with varying efficacy. In Australia, any chemical use must comply with relevant state and national legislation, as well as regulations imposed by the Commonwealth regulator, the Australian Pesticides and Veterinary Medicines Authority.

Acidic conditions suppress some diseases of nori (Ward *et al*. 2019) and regular acid washing of seaweed blades and cultivation nets has been used to control disease, but this is only partially effective for *Pythium* and ineffective at controlling Olpidiopsis blight (Kim *et al*. 2014). Chemical treatment, including acid washing, can also negatively affect the growth and product quality of seaweeds (Loureiro *et al*. 2015; Kerrison *et al*. 2016). Calcium salts have also been trialled to control water mould diseases, with calcium propionate applied at 10 mM for one hour found to be the most effective treatment for nori (Kim *et al*. 2023). Sodium dodecyl sulphate has been used to effectively treat water mould infection in Irish moss cultivation (Redmond *et al*. 2014).

Methods used to decontaminate material used for spore production or micropropagation (see above) typically result in physiological damage to the treated tissue, which is inconsequential for the purpose of reproduction or propagation, but unsuitable for cultivated material (Kerrison *et al*. 2016). Chlorine and iodine compounds and methanol have potential as decontaminants for some species, but it is important to assess the relevant tolerance of the cultivated species and target pests or diseases to candidate treatments to ensure they are safe and effective (Phillips 1990; Kerrison *et al*. 2016).

In countries with established seaweed industries, chemical treatments are rarely applied during at-sea seaweed cultivation because they are typically impractical to apply, environmentally undesirable, and, in many global seaweed-growing regions, illegal or highly regulated (Valero *et al*. 2017). Acid washing is, however, applied to *Pyropia* at sea in some Korean aquaculture regions using a vessel fitted with a large tub that is run along the cultivation nets, bathing each section for about 30 seconds (Kim *et al*. 2014). The short exposure time to the acid wash is likely responsible for the limited effectiveness of this method, and the practice is controversial, and banned in other aquaculture regions because of likely environmental impacts (Kim *et al*. 2014; Ward *et al*. 2019). The environmental impacts of treatments used in semi-closed and closed systems also need to be considered where treatment chemicals or by-products may be present in outflows (Phillips 1990; Valero *et al*. 2017).

Several treatments trialled to control bacterially mediated bleaching in *Gracilaria*, including povidone-iodine, hydrogen peroxide and sodium hypochlorite, were ineffective, while some antibiotics reduced the incidence of spontaneous bleaching but increased the risk of bleaching when treated specimens were exposed to pathogenic strains of bacteria (Weinberger *et al*. 1997). This is probably because of disruptions to seaweed microbiomes that play an important role in seaweed health and disease resistance (Weinberger *et al*. 1997; Qiu *et al*. 2019; Ling *et al*. 2022; Li *et al*. 2023), with some bacteria protective against disease (Li *et al*. 2022). There is a lack of understanding, however, of the typical bacterial communities of healthy seaweeds to compare with diseased specimens (Faisan *et al*. 2021). Studying the microbiomes of farmed and natural seaweeds could provide useful information to identify seaweed in poor health or to inform the use of microbiome manipulation to improve the health and disease resistance of seaweed crops (Li *et al*. 2023).

Secondary metabolites produced by some seaweeds may deter grazers and epiphytes, although some species are adapted to colonise or graze on chemically defended seaweeds (Behera *et al*. 2022a). Seaweed defensive chemistry also appears to play a role in disease prevention, and *Delisea pulchra* and *Gracilaria* spp. are more susceptible to disease when defensive chemistry is depleted (Campbell 2011). Monitoring seaweed secondary metabolites could therefore also assist in assessing health.

Where symptoms of disease occur, common diagnostic methods applied include culturing, DNA sequencing, and light and electron microscopy (Goecke *et al*. 2012; Diehl *et al*. 2017; Ward *et al*. 2019; Strittmatter *et al*. 2022). Many pathogens cannot be cultured with existing techniques, compromising the ability to diagnose and investigate seaweed diseases (Loureiro *et al*. 2015; Ward *et al*. 2019). Sequencing approaches, particularly 16S for bacteria, assist in characterising microbiomes and identifying bacterial strains associated with disease, although inoculation experiments are needed to confirm pathogenicity (Vairappan *et al*. 2001; Wang *et al*. 2007; Kumar *et al*. 2016; Ling *et al*. 2022). Sequencing and polymerase chain reaction (PCR) approaches (targeting the ITS and 18S, Cox1 and Cox2 genes) have also been used to identify water mould strains and *Maullinia* species (Goecke *et al*. 2012; Lee *et al*. 2015; Diehl *et al*. 2017; Badis *et al*. 2018; Badis *et al*. 2019; Mabey *et al*. 2021). These approaches have facilitated assessment of the range of occurrence of these pathogens, confirmed the identity of species infecting farms, and revealed cryptic diversity in some taxa (Lee *et al*. 2017; Badis *et al*. 2018; Badis *et al*. 2019). Molecular methods can also be applied to detect water mould zoospores in water (Lee *et al*. 2015). Targeted PCR approaches provide for rapid and accurate monitoring, but pathogens need to be genetically identified to enable to the development of relevant tests (Lee *et al*. 2017; Bernard *et al*. 2018a).

Domestication of farmed seaweeds has led to the development of strains with desirable characteristics, but the genetic diversity of these strains is low, contributing to their susceptibility to pathogens (Valero *et al*. 2017; Campbell *et al*. 2019b; Brakel *et al*. 2021; Murua *et al*. 2023). The need for healthy seed stock and disease-resistant strains has led to increasing interest in improving selective breeding techniques, including of commercially important vegetatively propagated seaweeds (Mantri *et al*. 2022; Bhuyan 2023). Clonal propagation has, however, selected strains that do not reproduce sexually, because these typically use resources for growth in place of reproduction (Valero *et al*. 2017). The lack of spawning assists in avoiding genetic recombination with wild stocks but makes genetic improvement difficult (Valero *et al*. 2017).

Techniques that are potentially useful for producing quality seed stock of clonally propagated seaweeds include tissue culture and micropropagation to produce axenic seed stock, and protoplast or cell-cell fusion techniques to produce new cultivars (Cottier-Cook *et al*. 2016; Chowdhury *et al*. 2022; Jiksing *et al*. 2022; Sugumaran *et al*. 2022). For Laminariales, selective breeding can be achieved by cloning gametophytes and carrying out controlled crossing with different levels of genetic relatedness, or between strains with desirable characteristics (Valero *et al*. 2017; Yarish *et al*. 2017; Chowdhury *et al*. 2022). Molecular identification may be useful to assist in strain selection for both red and brown seaweeds (Valero *et al*. 2017; Sugumaran *et al*. 2022). The development of disease-resistant stocks is, however, hindered by the lack of knowledge of how disease resistance is inherited, making selection of suitable characteristics difficult (Murua *et al*. 2023).

Local strains with good productivity or other desirable attributes should be selected for breeding, although it is important to consider the potential invasiveness of fast-growing genotypes (Stévant *et al*. 2017; Yarish *et al*. 2017; Largo *et al*. 2020a). Cultivars that may become invasive or pose an unacceptable genetic risk to wild stocks should only be grown in closed systems (Valero *et al*. 2017).

Breeding programs should also aim to ensure genetic diversity (Campbell *et al*. 2019b; Brakel *et al*. 2021; Cottier-Cook *et al*. 2021; Bhuyan 2023). Inbreeding should be avoided, and new genotypes introduced frequently (Nepper-Davidsen *et al*. 2021). Brood stock should be sourced from areas with high genetic diversity (Nepper-Davidsen *et al*. 2021) or reproductive material collected from several locations, although within the same biogeographic region, to provide diversity (Yarish *et al*. 2017). There is a need to increase understanding of seaweed genetic resources and the natural variation of wild stocks to facilitate breeding for genetic diversity (Loureiro *et al*. 2015; Brakel *et al*. 2021; Nepper-Davidsen *et al*. 2021).

The establishment of biobanks would be useful for strain preservation (Campbell *et al*. 2019b; Brakel *et al*. 2021; Chowdhury *et al*. 2022; Bhuyan 2023). Bio-banking of seaweeds presents challenges, however, due to their highly varied life histories and reproductive methods (Brakel *et al*. 2021).

Outcomes of the seaweed biosecurity planning workshop

Species, cultivation systems and regions of interest

The workshop discussions revealed that current interest is focused on commercialising *Asparagopsis* spp. (Figure 12) and golden kelp (Figure 13), with some cultivation of sea lettuce (*Ulva* spp.; Figure 14) and sea grapes (*Caulerpa* spp.), but that interest in other species is likely to develop. Operations are likely to cultivate multiple species, including potentially co-cultivating different seaweeds or cultivating seaweeds alongside other aquaculture species, including in IMTA systems. There is also interest is commercialising biofouling seaweeds, which would be collected by recruitment onto cultivation lines (Figure 15).

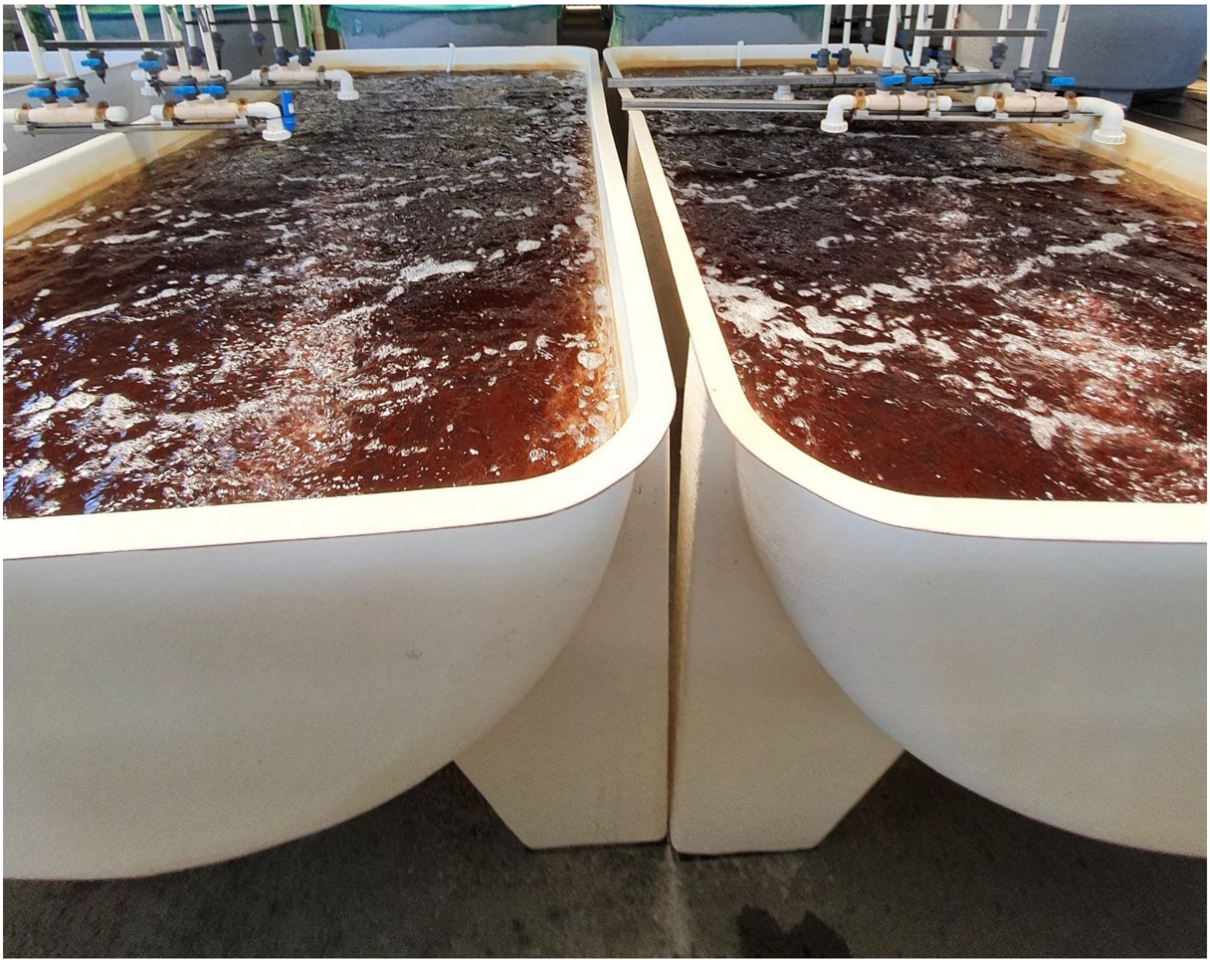

Figure 12. Cultivation of *Asparagopsis* spp. in land-based tanks. Photograph: Sasi Nayar, SARDI Aquatic and Livestock Sciences.

Land-based systems would potentially be either closed systems, which are defined as having a high level of control over water and stock, e.g., recirculating aquaculture systems, or semi-closed systems, which provide a high level of control over stock but less control over water than closed systems, e.g., flow-through tank or pond systems. Semi-closed systems that may be utilised include static tank or pond systems with periodic exchange. Closed and semi-closed systems would have varying levels of control over other inputs (e.g., nutrients) and environmental conditions (light, temperature, etc.) depending on their specific configuration. At-sea cultivation would typically be regarded as semi-open, i.e., having control over stock due to attachment to, or containment by, infrastructure, e.g., longlines, but with no control over water movement. Restoration and restocking activities would, however, be effectively open systems, i.e., with no control over stock after out-planting. Open and semi-open systems also typically offer no control over other inputs or environmental conditions, although semi-open systems, where the seaweed depth can be varied, provide some control over light.

Figure 13. Golden kelp growing on cultivation lines. Photograph: Jo Lane, Sea Health Products.

Cultivation is likely to initially take place in established aquaculture areas, but there is interest among operators in expanding to other locations. Most operations are likely to be either land-based or near-shore, but cultivation further off-shore is also of interest. There was also interest in inland aquaculture using saline groundwater.

Participants queried whether the guidelines developed would also be applicable to microalgae. It was noted that the project was specifically about biosecurity for the seaweed industry, and microalgae was therefore not specifically included. There is likely to be some overlap in biosecurity planning for microalgae and seaweeds, but the review of pests and diseases and workshop discussion did not include microalgae. There may, therefore, be additional or specific biosecurity concerns and activities involved with microalgae cultivation that are not covered by the guidelines developed in the project.

Key biosecurity threats

Biosecurity threats regarded as high priority by workshop participants include epiphytes and culture contaminants, pathogenic bacteria, and other disease agents (water moulds, viruses), risks associated with the co-introduction of pests and diseases, including those that could potentially impact species other than seaweeds, stock releases through reproduction or vegetative fragmentation, and the potential for genetic and ecological impacts.

Figure 14. Cultivation of sea lettuce in a land-based raceway tank. Photograph: Sasi Nayar, SARDI Aquatic and Livestock Sciences.

Diatoms, cyanobacteria, macroalgae and fungi were all noted as potentially important culture contaminants or epiphytes. It was recognised that diseases threats to Australian seaweed farming are not yet understood, but that disease issues would likely emerge as the industry develops. The effects of climate change on pests and pathogens, and on seaweed health, was also a concern. Pests or pathogens could be co-transported with seaweeds, and these could include pathogens of importance to other aquaculture species and wild organisms, and potentially pathogens or contaminants of concern to human health. It was noted that a separate project is investigating the food safety aspects of seaweed farming for human consumption, but that there was potential overlap with biosecurity planning where food safety risks are associated with organisms such as potentially toxic microalgae.

There was additionally consideration that farmed seaweed would provide increased biomass and density in some areas, which could lead to the proliferation of endemic seaweed pests or diseases, attract grazers, or increase the environmental load of pathogens of other species. The proliferation of some non-pathogenic microbes could also impact marine environments and species, e.g., sulphur reducing bacteria leading to hydrogen sulphide pollution.

Other concerns were the potential for ecological shifts to result from the introduction of farmed seaweeds to an area, particularly in the vicinity of sensitive environments or marine parks. Ecological shifts could result from escapes of farmed material (including through interbreeding with wild stock). Where escaped seaweeds or co-introduced seaweed pests or IAS establish, consideration of their impacts on marine environments should also include the food web and other flow-on impacts, e.g., displacement of seagrasses by invasive seaweed would lead to a loss of habitat for wildlife and a loss of food resources for species that feed on seagrass or seagrass-associated organisms.

Workshop participants also noted that seaweed aquaculture could have environmental impacts due to changed nutrient cycling or hydrodynamics, shading of surrounding habitat, or entanglement of wildlife. These potential impacts were noted to be important but outside the scope of biosecurity planning.

Figure 15. Collection of seaweeds occurring as biofouling on cultivation lines. Photograph: Sasi Nayar, SARDI Aquatic and Livestock Sciences.

Pathways for pest and disease spread

Pests and diseases can be introduced via seaweed stock, including brood stock, seed stock, reproductive material (e.g., gametes/spores), material harvested or introduced from other sites, and wild stocks, and by water, transport media, people and objects, such as equipment and vessels (Palić *et al*. 2015; SCAAH 2016; DAWE 2020; Cottier-Cook *et al*. 2022).

Key pathways for the introduction of pests and disease were discussed at the workshop. Participants agreed that stock movements were one of the most important pathways, and it was noted that wild-collected brood stock was likely to be commonly used to cultivate new species. Seed stock, including cuttings, fertile tissue, propagules (spores/gametes), gametophyte cultures and translocated mature stock, were also recognised as potential infection sources.

Water was also noted as a key pathway, with risks dependent on the system type. The locations of seaweed farms relative to other farms, wild seaweeds and other potential pest and pathogen sources, including effluent outflows and rivers, was recognised as important. Connectivity of the marine environment due to water movement was noted as an important consideration. Cross-contamination due to plumbing and drainage was a concern for land-based aquaculture. Inundation by floodwaters, storm surges or tides was also recognised as a pathway for pest or pathogen introduction.

Other pathways identified as important for aquaculture enterprise biosecurity were transport media; nutrients and other additives; cultivation equipment including substrates; other equipment; vehicles; vessels; people (staff, visitors and intruders); and wildlife and other animals. Nutrient addition is likely for some cultivation stages in land-based systems, but it was recognised that applying fertiliser at sea was undesirable and was likely to be ineffective in any case. Additional considerations included the potential use of carbon dioxide from effluent or other waste sources as a fertiliser for seaweed in bioremediation systems. Airborne contaminants were also considered a potential threat, including via aerosols generated within cultivation systems. Spawning of farmed seaweeds or escapes due to dislodgement of fragments or whole thalli were noted as important pathways for potential genetic or other environmental impacts on wild stocks.

Management strategies

Management strategies were discussed at the workshop, and as identified in the literature (Campbell 2011; Hudson and Egan 2022; Li *et al*. 2022; Murua *et al*. 2023), it was recognised that many seaweed diseases are due to opportunistic pathogens that may be infeasible to completely avoid or exclude. Furthermore, control and treatment options for seaweed diseases are scarce, and diagnostic methods need further development (Ward *et al*. 2019; Strittmatter *et al*. 2022).

Workshop participants agreed that preventing the occurrence of all pathogens would be impractical and that trying to remove all opportunistic pathogens would likely also result in the loss of beneficial microbes and be detrimental to seaweed health. It was therefore noted that appropriate husbandry will be very important to maintain seaweed health. Several mitigation measures were, however, identified, that will assist in reducing biosecurity risks. Important strategies to mitigate the identified threats and pathways include treating water appropriately, separating systems and different stocks, ensuring the health of incoming stock, implementing quarantine procedures, monitoring seaweed health, using dedicated equipment, training staff, and implementing cleaning and hygiene procedures. For at-sea cultivation, proximity to wild seaweeds and sources of pests and diseases should be considered when choosing farm locations. It was noted that cultivation systems used at sea would need to be designed to withstand rough weather or storm events to prevent losses of stock and infrastructure. Harvesting methodologies would also need to be developed or refined to prevent losses of material or the release of pest and disease propagules during harvest.

For closed and semi-closed systems, treatment of both incoming and discharged water was noted as important, with filtration and further treatment, e.g., ultraviolet sterilisation or chemical treatment, likely to be required. Whether treatment of both incoming and outgoing water (or either) was required would depend on the relative risks of pests and diseases being introduced to, or released from, the operation. Nutrient solutions should be purchased from reputable suppliers and records kept. It was noted that autoclaving could be used to effectively sterilise small batches of water, but nutrient solutions typically could not be heat-treated. Fine filtration of nutrients could be used to remove many contaminants. Incoming air and carbon dioxide may also need to be filtered. Suitable treatment of outflow water to prevent seaweed fragments or genetic material from escaping was regarded as important for semi-closed systems.

Site layout, separation of areas, barriers and security were noted as key strategies to mitigate risks involved with the movement of people, and to prevent intruders and wild animals from gaining access. Site layout and barriers would also help to prevent aerosol transfer. Air locks could be used if warranted. Specific, suitable personnel should be assigned to different areas and tasks, with access limited to particularly sensitive areas. The appropriate use of decontamination and personal protective equipment for staff moving between areas would also help mitigate risks.

The use of separate, dedicated equipment for different farm areas was regarded as important for preventing pest or disease spread within farms. It was noted, however, that some equipment, including tanks, ponds, vessels and equipment used for harvest and processing, would need to be used across multiple crop cycles and stocks. Suitable decontamination processes were recognised as critical to managing biosecurity risks for these items. Potential decontamination methods were discussed, including chemical treatments and sun-drying. Appropriate application of anti-fouling was noted as a strategy for vessels that were too large to regularly decontaminate out of the water. Pipework and delivery systems for other inputs should be cleaned regularly and filtration and other treatment systems maintained and regularly checked for effective operation.

For at-sea cultivation, site selection was regarded as critical, both to provide suitable conditions for the cultivated species and to avoid sensitive habitats or areas with high prevalence of seaweed pests or diseases. Proximity to wild seaweeds and to other activities that could vector pests and diseases will be important considerations. The arrangement of cultivation systems within farms will also be important to minimise risks of pests or diseases spreading with prevailing currents. If multiple species are to be cultivated, including in IMTA systems, consideration will need to be given to arrangement with respect to other species, e.g., to minimise the likelihood of fluke eggs from fish aquaculture accumulating on seaweed cultivation infrastructure. Where multiple seaweed species may be co-cultivated, it will be important to understand the likelihood of shared pests or pathogens. It was noted that cultivation of multiple species could also involve different species being cultivated at different times throughout the year, or crop rotation between years.

It was recognised that suitable local cultivars should be used in semi-open systems or for restoration. Where hatcheries are used to produce seed stock for out-planting, the current practice in South Australia is to collect wild brood stock from the same defined management area as the lease site. Suitable cultivars would ideally be disease-resistant, suitable for biotic conditions in the growing area, genetically diverse, and not genetically differentiated from local wild seaweeds. The use of sterile seaweeds for out-planting, timing planting to avoid reproductive periods, and harvesting material prior to reproductive maturity were also discussed as strategies to prevent farm-to-wild gene flow from at-sea farms. It was noted that some strains may only be suitable for cultivation in closed systems. To prevent losses due to infrastructure breakage, it will be important to ensure systems are robust for the conditions in which they will operate, noting that times of storm activity may need to be avoided in determining suitable culture periods. Operating during a suitable cultivation period will also assist in minimising fouling growth.

Ensuring seaweed health prior to out-planting will be important for at-sea cultivation and for restoration and restocking activities. Out-planted material should be selected or treated to be free of seaweed pests, pests or pathogens of other species, and invasive aquatic species. To avoid co-introductions in transport media, either filtered, sterilised water or water from the source location should be used. Current practices include maintaining hatchery-produced seedlings for several days in filtered (0.2 µm) seawater prior to out planting. Production breaks, fallowing or strategic crop rotation may be applied in at-sea cultivation to break infection cycles.

Workshop participants noted that contingency planning for seaweed aquaculture is limited by the current lack of knowledge on specific diseases that will impact the Australian seaweed industry. Diagnostic methods and expertise will also need to be developed. It was noted that microscopy, culturing and DNA sequencing were likely to be useful diagnostic tools. Once specific pests or pathogens of Australian seaweeds are identified, targeted molecular approaches (e.g., PCR) could be developed and used for rapid diagnosis and surveillance.

The need to have defined criteria to trigger action and strategies to address outbreaks was recognised. Key signs of seaweed pest and disease outbreaks that might trigger a response were discussed. These signs include colour change, necrosis, mortality or loss of biomass, lesions or galls, and changes to water quality. Understanding normal growth rates, mortality rates and appearance will be important. It was noted that biosecurity plans should include information on stock inspection frequency, responsible parties and what data to collect. Microbiome monitoring or environmental DNA monitoring were considered as potential future strategies that would need to be developed.

Considerations for response include isolation/containment, sampling for diagnostics, emergency harvest, disposal methods, back-up systems, reporting and communication. It was recognised that emergency harvest could involve large volumes of material. Stock harvested for biosecurity purposes could still be useful or saleable, but utilising the stock would potentially require storage for large volumes. Disposal methods for unusable or excess stock include composting, such as was applied to dispose algal bloom material (Winberg 2011). Methods and suppliers to transport large volumes generated by an emergency harvest would need to be identified.

Determining the genetic identity of cultivated species was an important concern for workshop participants. The importance of using standardised names was also recognised. Understanding genetic structure and diversity was recognised as useful for selective breeding, as well as for informing biosecurity risks. Bio-banking of natural and selectively bred strains was discussed as a strategy to mitigate genetic risks. It was recognised that broadscale monitoring would be required to detect cryptic invasions or genetic effects, and that prevention was important.

It was noted that information on the genetic structure of populations was available for a limited number of Australian seaweed species. Work in this area is ongoing but additional research is likely to be needed to determine the genetic structure of seaweeds of commercial interest. Centralised hatcheries are likely to be used for seed stock production, hence it will be important to track the provenance of brood stock material, maintain separation of stocks from different areas, and ensure material used for out-planting is derived from local brood stock to avoid genetic impacts.

The co-cultivation of multiple species, including in IMTA systems, was recognised as potentially benefiting crop performance, but also carried biosecurity risks that were not well understood. It was noted that further investigation of interactions between co-cultivated species was needed to inform management. Managing these risks will involve strategies applied to seaweed and to other co-cultivated species. Biosecurity planning for other aquaculture industries will therefore also need to consider seaweeds where co-cultivation is of interest. There will also need to be cooperation between operators within aquaculture zones, including across different aquaculture industries.

Workshop participants noted that some issues would be considered in broader planning frameworks, rather than within industry or enterprise biosecurity plans. These issues include the management of co-cultivation risks or other cross-industry impacts where different aquaculture crops are grown within an aquaculture area or zone. Some ecological risks associated with seaweed aquaculture (e.g., changed nutrient cycling, altered water quality, light availability or hydrodynamics, and entanglements) were similarly recognised as important but needed to be covered by environmental management frameworks rather than enterprise biosecurity. Biosecurity plans should, however, complement strategies that seek to address these other risks.

Summary and conclusions

Diseases, parasites and pests cause serious production losses for the global seaweed industry, and often have detrimental environmental effects. Effective biosecurity is essential to secure productivity and prevent the negative impacts of aquaculture, such as disease and pest introduction, including of IAS, and genetic influence on wild stocks.

Despite recognition of biosecurity threats, biosecurity management in the seaweed industry is hampered by a general lack of information, including poor understanding of causative agents and pathways for seaweed disease, limited research on disease prevention or treatment, lack of clear genetic identity of cultivated seaweed varieties, and limited knowledge of the genetic structure of wild populations (Campbell *et al*. 2019a; Ward *et al*. 2019; Campbell *et al*. 2022; Murua *et al*. 2023). Applying standard biosecurity practices and precautionary approaches does, however, reduce biosecurity risks, even where knowledge is lacking (Kambey *et al*. 2021c).

Appropriate policies and regulation, adapted to the needs of the seaweed industry, are required to mitigate biosecurity risks and realise the benefits of seaweed farming while avoiding negative impacts on both aquaculture enterprises and the environment (Stévant *et al*. 2017; Cottier-Cook *et al*. 2021; Spillias *et al*. 2022). To develop effective policies and regulation, it is important to identify cultivated species, their diseases and pests, any high-risk practices, and practical measures that can be applied to address key risks (Cottier-Cook *et al*. 2022).

Knowledge of diseases, parasites and pests, and environmental biosecurity concerns affecting global seaweed aquaculture has been provided by this project. This report is a guide to the types of pests and diseases likely to affect the emerging Australian seaweed industry, despite most species considered for cultivation in Australia being different from those grown in other regions (these being predominantly non-native to Australia). Opportunistic bacteria, water moulds, parasitic endophytes, macro-epiphytes, and grazers are common pathogens and pests across many seaweed taxa. Protozoa, fungi and viruses also negatively impact several farmed seaweed species. As aquaculture of novel species is developed and seaweed cultivation intensifies, new diseases, parasites and pests are likely to emerge, and known pests and pathogens may behave differently in new areas (Ward *et al*. 2019; DAWE 2020; Murua *et al*. 2023). Current understanding of seaweed viruses is particularly limited, and further viral diseases are likely to be discovered as industry intensifies, investigations continue and diagnostic technologies advance. Aquaculture activities provide a risk of IAS introduction and spread, with risks from seaweed aquaculture including the potential for farmed seaweeds to become invasive or for other IAS to be introduced via seaweed stock, in water (including transport media) or on equipment (Naylor *et al*. 2001; Williams and Smith 2007; Campbell *et al*. 2019b; DAWE 2020; Cottier-Cook *et al*. 2021; Tonk *et al*. 2021; Bhuyan 2023).

Characterising endemic diseases and opportunistic pathogens, and their prevalence in wild populations will be important for understanding risk and informing site selection. Determining suitable growth conditions for seaweeds cultivated in Australia will also assist operators in selecting suitable sites and reducing the likelihood of environmentally mediated diseases. Site selection should also aim to avoid sensitive habitats that may be adversely impacted by seaweed aquaculture. Developing methods and capacity for surveillance and diagnostics will be paramount to characterise endemic pathogens and facilitate early identification of emerging diseases, parasites and pests. Investigation of seaweed genetic resources and structure in Australian populations will also be important to underpin brood stock selection and inform genetic risks.

A biosecurity action plan and guidelines for the seaweed industry have been developed using the information compiled by this project and incorporating feedback from stakeholders. Given the current lack of information on specific pests and diseases of importance to the Australian seaweed industry, and the fact that the Australian seaweed industry may develop around multiple seaweed species, including novel species, biosecurity planning will need to be flexible and adopt generic management strategies and precautionary approaches. As industry develops and knowledge of specific pests and diseases increases, approaches can be refined and targeted mitigation strategies can be applied.

Implications for industry

Knowledge on biosecurity issues relevant to the emerging Australian seaweed industry has been obtained by this project, and management strategies to mitigate relevant risks have been identified.

Enterprise biosecurity guidelines for seaweed industry have been developed in consultation with industry, government and research stakeholders. These guidelines provide a flexible framework that facilitates seaweed industry enterprises to develop and implement biosecurity plans that suit their operation. The adoption of biosecurity management by seaweed industry will assist enterprises in ensuring the good health and performance of cultivated seaweed, facilitate early detection of disease outbreaks and reduce their impact, obtain or maintain market access, fulfil regulatory requirements, and support the environmental sustainability of seaweed aquaculture.

Biosecurity plans manage risks pertaining to biological agents, including seaweeds themselves and pest and disease organisms that may be co-introduced or promoted by seaweed industry activities. Enterprises will typically have additional environmental and other management requirements, such as those relating to chemical use, potential ecological impacts not caused by biological agents (e.g., due to shading, changed nutrient cycling or hydrodynamics, entanglements), work health and safety, food safety, and interactions with other industries and marine activities. Risk management for these aspects will usually involve broader frameworks and will not directly be addressed by biosecurity plans. Strategies to address these aspects is therefore not specifically covered in the biosecurity guidelines included in this report as an appendix. Biosecurity plans, should, however, aim to integrate with and complement these other frameworks and requirements.

Recommendations for industry

The biosecurity guidelines developed by this project and the supporting information contained in this report provide seaweed industry enterprises with tools to develop enterprise-level biosecurity plans.

It is recommended that all seaweed industry enterprises develop and implement biosecurity plans that are tailored to their operation, even where this is not a specific requirement of their licence or permit conditions, or jurisdictional legislation.

The current lack of knowledge on specific pest and disease issues that will affect Australian cultivated seaweeds, and the fact that industry may develop around multiple species, including some not yet under consideration, means that flexible and precautionary approaches will be needed for biosecurity management, at least initially. Collating and sharing information on pest and disease issues as these arise will assist industry in refining biosecurity knowledge and practices. The guidelines focus on generic approaches valuable for all aquaculture industries to protect against unforeseen biosecurity threats. But where specific pest or disease issues occur, diagnostic methods and tailored management strategies should be developed and incorporated into future industry biosecurity planning.

Continued investment in research and development as the Australian seaweed industry matures will assist in ensuring biosecurity knowledge, diagnostics, treatment and management strategies are available and keep pace with industry needs.

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Appendix 1. Contact list for reporting seaweed biosecurity issues

At the time of publication, there are no specific notifiable seaweed diseases, but seaweed aquaculture enterprises are required to report suspected disease occurring in cultivated species in most jurisdictions.

Biosecurity incidents or concerns, including suspected invasive aquatic species, should also be reported. Operators should ensure they understand reporting obligations and licence or permit conditions for their activities, and maintain up-to-date contact information. Current key jurisdictional contacts are provided below.

Western Australia

Where disease is suspected in organisms grown under permit or exemption in Western Australia, the Department of Primary Industries and Regional Development must be notified on 1300 278 292

South Australia

In South Australia, requirements for notification where unusual mortality occurs or the licensee knows, or ought reasonably to know, that any cultivated organism is affected with disease are provided under regulation 13 of the *Aquaculture Regulations 2016*. Specifically, notification of unusual mortality or suspected disease must be made by telephone call to the number provided to the licensee for that purpose. There are also requirements under regulation 14 to control aquatic organisms affected with disease.

Suspected invasive aquatic species should be reported to the 24-hour Fishwatch hotline by calling 1800 065 522. More information on Fishwatch is available on the PIRSA website.

Victoria

Suspected seaweed diseases in Victoria should be reported to the Chief Veterinary Officer at the Department of Energy, Environment and Climate Action via cvo.victoria@agriculture.vic.gov.au or to the 24-hour Emergency Animal Disease Hotline by calling 1800 675 888.

Invasive aquatic species should be reported to marine.pests@agriculture.vic.gov.au.

Tasmania

In Tasmania, permit and licence holders must report any suspected marine plant diseases to an authorised Biosecurity Tasmania Officer and notify the General Manager (Marine Resources) at the Department of Natural Resources and Environment Tasmania by calling 03 6165 3777.

Disease diagnostic support is provided by Plant Diagnostic Services at Biosecurity Tasmania, part of the Department of Natural Resources and Environment Tasmania. Contact them by emailing PlantDiagnosticServices@nre.tas.gov.au.

New South Wales

In New South Wales, reports of suspected disease in cultivated seaweed should be made to the Department of Primary Industries via the Emergency Disease Hotline by calling 1800 675 888, or by email to Aquatic.Biosecurity@dpi.nsw.gov.au.

Diagnostic support is provided by the Elizabeth Macarthur Agricultural Institute, phone: 02 4640 6333.

Queensland

Aquaculture operations in Queensland are obligated under the *Biosecurity Act 2014* to take reasonable and practical measures to minimise the risk and spread of disease. Suspected disease or unusual mortality in cultivated seaweed should be reported to Biosecurity Queensland by calling 13 25 23.

Northern Territory

In the Northern Territory, reports of suspected disease in cultivated seaweed should be made to the Aquatic Biosecurity Unit by calling 0413 381 094 or emailing AquaticBiosecurity@nt.gov.au.

Appendix 2. Seaweed Industry Biosecurity Action Plan

The goal of the *Seaweed Industry Biosecurity Action Plan* is to promote a profitable and sustainable Australian seaweed industry by protecting the health and performance of cultivated seaweeds and by safeguarding aquatic environments against biosecurity threats posed by the industry.

Objectives

The objectives of the action plan are:

- Minimise the risk of seaweed pathogens and pests negatively impacting cultivated seaweed health, productivity and crop quality.
- Mitigate environmental biosecurity risks to prevent the spread of pests and diseases, invasive aquatic species, and genetic impacts on wild seaweeds.
- Maintain market access and social licence to operate.
- Ensure that regulatory frameworks exist for seaweed cultivation and related activities that support the biosecurity of both the seaweed industry and aquatic environments.

Action items

Key actions to support the objectives of the action plan are provided in Table 3. The biosecurity planning guidelines developed as part of this project provide seaweed industry enterprises with the necessary tools to develop biosecurity plans to achieve the action plan objectives at an enterprise level. Implementing biosecurity planning widely across the Australian seaweed industry as this develops will assist in the proactive management of biosecurity threats to support the action plan goal and objectives.

The Australian seaweed industry is at an early stage of development, and, while knowledge of important types of seaweed pests and diseases has been obtained, the specific pests and diseases of greatest import to Australian seaweed industries are not yet known. New pests and diseases are, furthermore, likely to emerge or be identified as the industry develops and seaweed diagnostic technologies improve. Seaweed industry biosecurity management should seek to continually improve by investigating pest and disease issues as these arise, increasing knowledge of health status and the genetics of wild stocks, and refining management approaches as knowledge and technology improve. Generic biosecurity measures will, however, remain relevant to protect against unforeseen and emerging threats, and mitigate the impacts of opportunistic pathogens that are common causative agents for seaweed disease.

Key barriers to achieving the action plan goals are the lack of a peak seaweed industry body, access to seaweed disease diagnostic services, and the suitability of current regulatory frameworks for seaweed biosecurity. The establishment of a peak industry body and frameworks would assist in disseminating and refining biosecurity planning guidelines. Regulators and industry should work together to advance seaweed biosecurity management and develop processes for auditing biosecurity performance.

Table 3. Actions to support the *Seaweed Industry Biosecurity Action Plan*, including progress to date, requirements and potential barriers.

Action	Progress	Requirements	Barriers
Implement farm biosecurity measures	Biosecurity planning guidelines have been developed that will allow farms to develop effective biosecurity plans and manage biosecurity risks.	Widespread dissemination of the guidelines. Operators will need to develop enterprise-level biosecurity plans, using the guidelines, that are tailored to their operations.	Lack of a mature peak industry body to guide industry-level biosecurity planning and disseminate the biosecurity guidelines.
Further develop knowledge on seaweed pests and diseases relevant to Australian species and environments	Baseline knowledge on important types of seaweed pests and diseases has been obtained. Important signs of pest and disease problems that should trigger investigation are understood. Knowledge of the specific diseases and pests of Australian seaweeds is still lacking.	Monitoring the health status of cultivated seaweeds and investigating pest or disease issues that arise. Developing specific treatments for pests and diseases. Knowledge of the health status of wild stocks and the likelihood of pest and disease transmission to and from farmed stock.	Limited access to seaweed disease diagnostic services. Difficulty identifying specific causes of disease due to seaweed diseases potentially being environmentally mediated. Investment to build knowledge on seaweed pests and disease is needed.
Further develop knowledge to manage environmental biosecurity	Environmental biosecurity risks are understood, but due to a lack of knowledge on the disease status and genetic structure of wild stocks, precautionary approaches are needed.	Knowledge of the prevalence and distribution of pests and diseases in wild seaweed stocks. Increased knowledge of the genetic structure and diversity of Australian seaweeds.	Limited access to seaweed disease diagnostic services. Investment to build knowledge on how to manage environmental biosecurity is needed.
Refine biosecurity management strategies and frameworks	Generic management strategies have been identified that protect against unforeseen pest and disease threats, and which can minimise losses due to opportunistic pathogens that are impractical to completely exclude from cultivation. Decontamination and quarantine procedures applied in seaweed aquaculture globally are likely to be applicable but should be assessed for their efficacy in Australian systems.	Knowledge of preventative measure and treatments for specific pests and diseases that affect Australian seaweeds. Knowledge of the efficacy of decontamination and quarantine procedures. Regulatory frameworks to support industry and environmental biosecurity. Biosecurity frameworks should align with those of other aquaculture industries and complement other frameworks (e.g., broader environmental management, work health and safety).	Specific pest and disease issues for Australian seaweeds are not yet understood. Treatment options will remain limited for open and semi-open systems. The agency responsible for managing seaweed biosecurity in some jurisdictions is not yet established. Appropriate legislative frameworks for seaweed cultivation and biosecurity may be lacking. Lack of a mature peak industry body to streamline endorsement of refined plans and work with regulators to ensure frameworks are appropriate.
Audit and review the effectiveness of seaweed industry biosecurity management	The biosecurity guidelines provide an auditable framework.	Operator auditing of their biosecurity plans, following the guidelines. Independent auditing where stronger assurance of biosecurity control is required by customers or regulators.	Independent auditors for seaweed biosecurity may not be readily available.

Appendix 3. Seaweed Aquaculture Farm Biosecurity Plan: Guidelines and Template

The biosecurity planning document provided in this appendix is designed so that it can be read as a standalone document. It therefore summarises or replicates some information from the main report.

Seaweed Aquaculture Farm Biosecurity Plan

Guidelines and Template

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Nicole Thompson, Jason E. Tanner,
Sasi Nayar and Marty R. Deveney

May 2024

Part 1 General information

1 Introduction

These guidelines have been developed to provide the Australian seaweed industry with tools and templates to enable seaweed farms to develop biosecurity plans.

Enterprise biosecurity plans assist farms in managing biosecurity risk and may also assist in fulfilling biosecurity requirements for movement and trade in seaweed. These guidelines have been developed as part of the AgriFutures Australia project *Biosecurity for the Australian seaweed industry* (project number PRO-017299). They have been developed:

- in accordance with the national Aquaculture Farm Biosecurity Plan: generic guidelines and template;
- with input from industry consultation and a stakeholder workshop held on 13 December 2023;
- with additional support from the Fisheries Research and Development Corporation project, *Developing biomass assessment approaches, harvest methodologies and biosecurity knowledge for wild-harvest of seaweeds in southern Australia* (project number 2021-112).

This document aims to guide the development of biosecurity plans for application at the farm level. The information within the guidelines will, however, also be useful to assist the development of industry biosecurity frameworks. These guidelines have been developed to target seaweed aquaculture and cultivation systems for seaweed generally, rather than for specific seaweed types. It is anticipated that this document will be adapted for the purposes of specific seaweed types or production systems (see Section 2). These guidelines have been developed specifically for seaweed (macroalgae) rather than for algal cultivation more generally, which also includes microalgae. Much of the information within the guidelines will be applicable to microalgae, however microalgal cultivation may have additional biosecurity considerations and requirements not captured in these guidelines.

Disease is an inevitable part of aquaculture production, including for seaweeds. Some pathogens are always present in farmed stock and only cause disease when the right conditions occur, such as when environmental conditions are suboptimal for cultivated seaweed. The impact of these pathogens can typically be managed with good hygiene and husbandry. Other pathogens can be very damaging even under ideal husbandry conditions; these should be excluded from your farm wherever possible.

Worldwide, there is an increasing risk of significant aquatic diseases emerging and spreading. New diseases can emerge due to increasing aquaculture production, production in new locations, production of new species, and new production methods, all of which are applicable to the Australian seaweed industry. Diseases can also spread due to increasing international seafood trade volumes, movement of stock (for human consumption or aquaculture), trade of aquaculture equipment, shipping, and changes in climate.

Seaweed aquaculture production globally is also impacted by pests, including culture contaminants, parasitic endophytes, epiphytes and grazers. Here, the term ‘pests’ refers to organisms that negatively impact seaweed aquaculture, with these pests being potentially either native or introduced species. Seaweed pests affect production through competing with cultivated seaweeds for space, light and/or nutrients (contaminants and epiphytes), or through consuming seaweed tissue (grazers). Damage caused by grazers and parasitic endophytes may also increase susceptibility to disease, and pests of all types may reduce product value due to damage or contamination. Pests should therefore be excluded from seaweed cultivation systems as far as practical.

Seaweed aquaculture activities may also pose biosecurity risks through the introduction of invasive aquatic species (IAS), which are non-native species that can severely impact aquaculture, fisheries and the natural environment. Seaweed pests may also negatively impact wild stocks if released from, or promoted by, seaweed cultivation. Governments and industry share responsibilities for managing the risks associated with the spread of aquatic invasive species, aquaculture pests and aquatic diseases.

Biosecurity describes the systems put in place to protect your farm and the environment from pests and diseases. These systems can reduce the risk of damaging pests and diseases entering your farm, can prevent health issues emerging within the farm, and can reduce the impacts of pests or diseases when these occur. Good biosecurity practices can assist in meeting requirements for stock translocations and trade, in preventing environmental harm, and in fulfilling aquaculture licence conditions and general biosecurity obligations where applicable.

Sound biosecurity practices are good for business because their cost can be low compared to the expected benefits for productivity and product quality. This is particularly the case when serious pests and diseases can be excluded from your farm, or eradicated if they occur. Figure 16 shows a hypothetical invasion curve for a pest or disease entering and spreading in a new environment. As the pest or disease spreads, the return on investment from management interventions decreases. Preventative biosecurity actions that exclude damaging pests and pathogens from entering your farm usually provide the best return on investment.

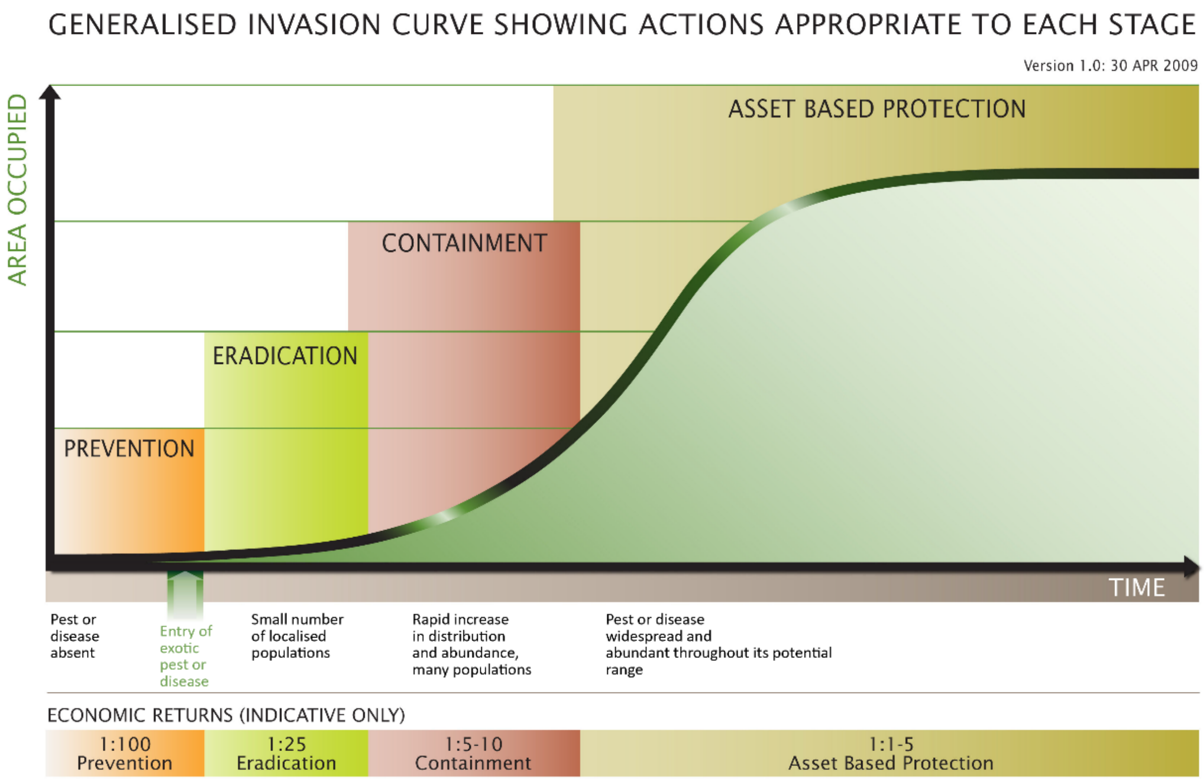

Figure 16. Hypothetical invasion curve for an IAS or disease spreading in a new environment. Adapted from: DPI Victoria. (2010). *Invasive Plants and Animals Policy Framework*. Department of Primary Industries Victoria, Melbourne.

1.1 Why develop a biosecurity plan?

The main reason to develop a biosecurity plan is that it is good for your business. Good biosecurity practices can support farm productivity, product quality, trade and ultimately profitability.

Improved biosecurity practices can:

- result in better stock health and improved growth performance and product quality;
- mitigate the transmission and amplification of diseases within/between farms or growing areas;
- allow for early disease, pest and IAS detection so that impacts can be avoided or reduced;
- support claims of freedom from diseases that impact marketability and market access;
- be integrated with other farm quality control systems such as hazard analysis critical control point (HACCP);
- facilitate translocation within and between jurisdictions;
- allow farms to meet international trade requirements (e.g., through health accreditation);
- be integrated with broader risk management planning, such as workplace health and safety, food safety and environmental management.

Aquaculture enterprises are linked through the movement of people, stock, equipment, waste and water. Through these movements, risks are shared and disease outbreaks in any region, farm or hatchery can affect others and threaten an entire sector. For this reason, producers in an individual sector should share responsibilities for biosecurity by aspiring to a common level of risk management.

Some jurisdictions have regulatory requirements for biosecurity that are legislated or are part of licence conditions. Those should be considered in the development of individual biosecurity plans.

Biosecurity plans assist in preventing environmental harm caused by pests and diseases. Preventing environmental harm assists in ensuring the sustainability of aquaculture operations, in maintaining social licence, and in fulfilling aquaculture licence environmental conditions and other legal obligations. Biosecurity plans manage risks pertaining to biological agents, including seaweeds themselves and pest and disease organisms that may be co-introduced or promoted by seaweed industry activities. Enterprises will typically have additional environmental and other management requirements, such as those relating to chemical use, potential ecological impacts not caused by biological agents (e.g., due to shading, changed nutrient cycling or hydrodynamics, entanglements), work health and safety, food safety, and interactions with other industries and marine activities. Risk management for these aspects will usually involve broader frameworks and will not be directly addressed by biosecurity plans. Biosecurity plans should, however, aim to integrate with and complement these other frameworks and requirements.

1.2 Purpose of a biosecurity plan

The purpose of an aquaculture biosecurity plan is to:

- reduce the risk of pests and diseases being introduced into your farm (entry biosecurity);
- reduce the risk of pests and diseases spreading or proliferating within your farm (internal biosecurity);
- reduce the risk of pests or diseases escaping from your farm (exit biosecurity);
- have emergency response protocols in place for serious pest or disease outbreaks (all three biosecurity components);
- Reduce the risk of your farm activities introducing or spreading IAS.

Figure 17 illustrates the entry, internal and exit components of farm biosecurity.

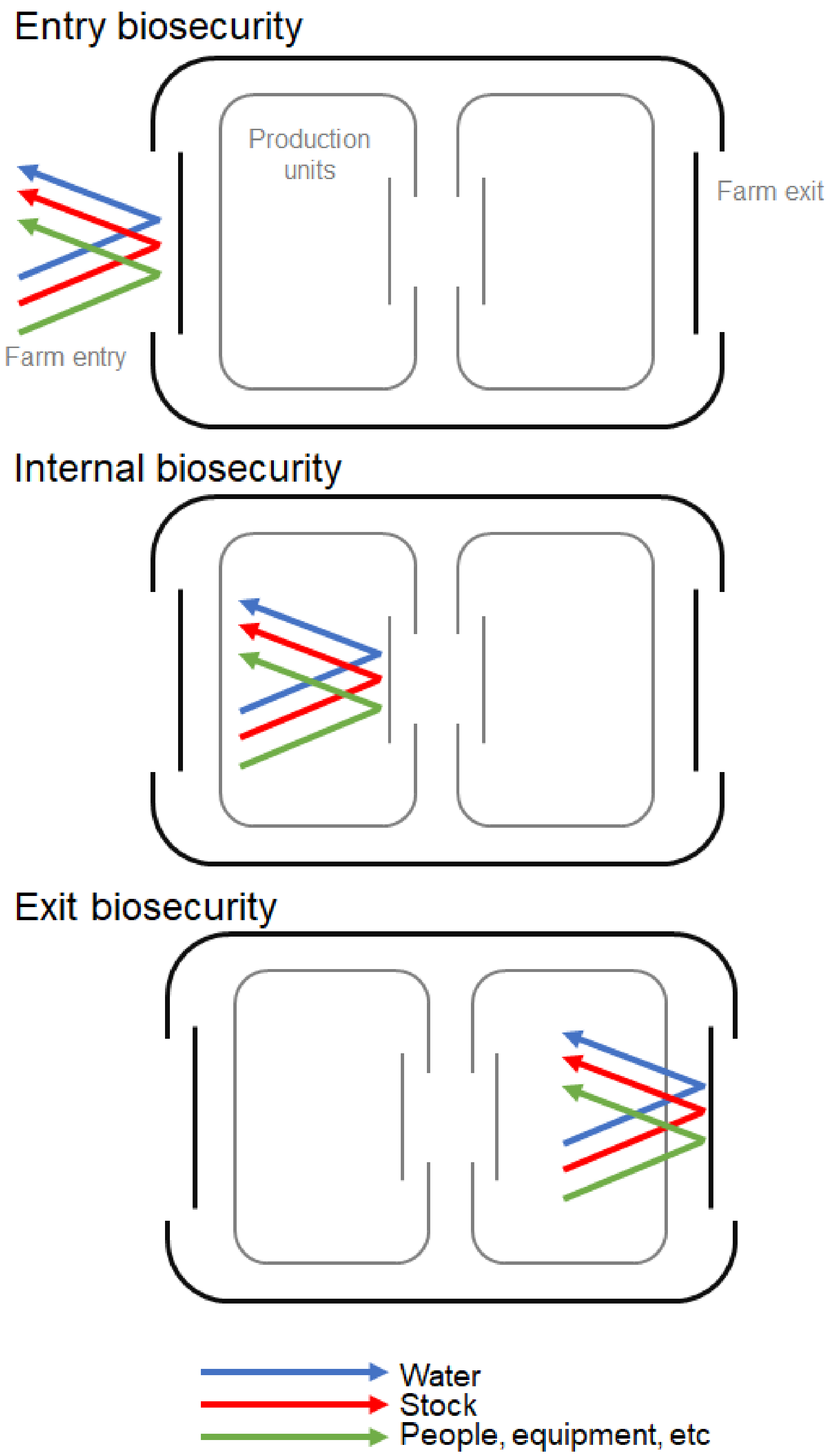

Figure 17. Key components of farm biosecurity.

Biosecurity plans need to be fit for purpose and balance practicality, cost and regulatory requirements. Ultimately, the proposed biosecurity practices should improve the biological, operational and economic performance of your farm. Good biosecurity practice should be as simple and low cost as possible to achieve the desired outcomes. Ultimately, biosecurity plans should be viewed as insurance; as such, they require both financial and intellectual investment, as well as commitment.

1.3 Using these guidelines

This document was developed to encompass existing practices used in seaweed aquaculture globally. As the Australian seaweed industry develops, these practices are likely to be modified for the Australian context and for the specific seaweed types being cultivated, and new practices are likely to be developed and adopted. Biosecurity planning for the seaweed industry will therefore continue to evolve, and enterprises should continue to update their plans. New enterprises should collate up-to-date information on current seaweed industry biosecurity practices when adapting this document to develop their biosecurity plans.

To develop an effective biosecurity plan, farmers need to consider several factors. These guidelines provide information, as well as templates and other resources, to help you assess risks for seaweed farms. This will help you develop a biosecurity plan tailored for your farm.

Every farm is different, and pests and disease risks need to be managed according to the circumstances of each individual farm. It is therefore important that a specific, documented and auditable biosecurity plan is developed for your farm. The plan should be updated as farm circumstances and disease risks change.

This document will assist you to:

- identify and assess biosecurity risks to your farm;
- develop procedures to manage biosecurity risks;
- manage and reassess these risks on an ongoing basis.

Each farm will have a different spectrum of biosecurity challenges and operating environments because of variations in:

- the number and type of species and life stage(s) farmed;
- the type of cultivation system used;
- the operation size;
- the farm location and layout;
- the disease, pest and IAS status of the region or state/territory;
- the proximity to wild seaweed populations and other aquaculture sites;
- available resources.

You will need to develop an individual farm biosecurity plan that takes your farm's uniqueness into account. This ensures that the plan is practical for your operation, as well as being as simple and low cost as possible to achieve desired biosecurity outcomes.

The guidelines provide supporting documentation and templates as appendices to help you develop your plan. You will need to tailor some documents specifically for your farm. You will not need to duplicate existing documents, systems or records, but, where appropriate, reference these within your biosecurity plan.

A biosecurity plan template is included in Part 5 and can be used to develop a biosecurity plan for your farm. The document excludes biosecurity planning at the industry and regional level (e.g., inter-regional movement) but could contribute to plans at those levels.

1.4 Steps to develop an aquaculture farm biosecurity plan

The key steps to developing a biosecurity plan are:

1. Compile farm information, including farmed species and cultivation system (Section 2).
2. Determine the major pest and disease hazards to your farm (Section 3).
3. Consider the major transmission routes onto, within and from your farm (Section 4).
4. Perform a risk assessment (see Part 3 of this document) for each hazard, considering transmission routes. The risk assessment considers, in the absence of any mitigation measures:
    a. the likelihood of a pest or disease occurring;
    b. consequences should that pest or disease occur.
5. Use the risk assessment to determine appropriate risk mitigation management actions for each hazard. Where the risk level is negligible or low without specific mitigation, no management is required, but ongoing monitoring is advised to determine whether the risk profile changes. Where the risk level is medium or above, management actions are required to mitigate risks. Actions should be practical and economic, and commensurate to the level of risk, i.e., more intensive mitigation measures will be needed where the risk is high to extreme than where the risk is medium.
6. Document the farm biosecurity plan, including how risk mitigation measures will be applied to address risks. See Part 2 of this document for details of what should be included in the biosecurity plan.
7. Implement the biosecurity plan measures on your farm.
8. Implement a review cycle for your biosecurity plan.

Table 4. Risk categories used to inform management. See Section 11 for information on how to carry out a risk assessment.

Risk level	Explanation and management response
Negligible	Acceptable level of risk. No action required.
Low	Acceptable level of risk. Ongoing monitoring may be required.
Medium	Unacceptable level of risk. Active management is required to reduce the level of risk.
High	Unacceptable level of risk. Intervention is required to mitigate the level of risk.
Extreme	Unacceptable level of risk. Urgent intervention is required to mitigate the level of risk.

2 Farmed species and cultivation systems

Seaweeds comprise a wide range of taxonomic groups with varying, and often complex, life histories. Globally, seaweeds are farmed for food, extracts (e.g., hydrocolloids and bioactive compounds) and a range of other purposes, including for animal feed and biofuel production.

The Australian seaweed industry will develop around native species, most of which will not be species that are farmed elsewhere, due to established farmed species not occurring naturally in Australia. The species cultivated in Australia are, however, likely to include several that are closely related to species cultivated elsewhere, due to their ability to meet existing market demands. These species are likely to be cultivated using systems adapted from established methods used for related farmed species. Native species not closely related to those farmed elsewhere may also be developed for cultivation in Australia, particularly where these seaweeds produce novel compounds of commercial interest, e.g., *Asparagopsis* spp. Because the Australian seaweed industry is developing, these biosecurity guidelines draw on information from established seaweed industries elsewhere.

Some key types of seaweeds farmed globally or for which aquaculture is developing in Australia are summarised below. Further detail can be found in the final report for the AgriFutures Australia project PRO-017299 *Biosecurity for the Australian seaweed industry*.

2.1 Large brown seaweeds

Cultivated large brown seaweeds include Laminariales: kombu (*Laminaria* and *Saccharina* spp.); wakame (*Undaria pinnatifida*); and, to a lesser extent, Fucales: bull kelps[4] (*Durvillaea* spp.) and hijiki *(Sargassum fusiforme*). Laminariales have a two-stage life cycle with a microscopic gametophyte stage and macroscopic sporophyte, while Fucales produce gametes, with zygotes that develop directly into the next generation of adults. Neither Laminariales nor Fucales regrow from cuttings. Cultivation of these seaweeds typically involves a hatchery and/or nursery stage where spores or gametes are seeded onto lines and grow to small juveniles, followed by out-planting at sea until harvest. For Laminariales, gametophytes may be vegetatively cultured to increase the quality and quantity available for seeding, to allow out-planting in seasons outside normal reproductive periods, or to allow crossing of selected strains.

2.2 Red seaweeds

Hydrocolloid (carrageenan and agar) producers

Farmed carrageenan-producing seaweeds include members of the order Gigartinales: jellyweeds (*Betaphycus*, *Eucheuma* and *Kappaphycus* spp.) and Irish moss (*Chondrus crispus*). Farmed agar producers come from the order Gracilariales, including *Agarophyton*, *Gracilaria* and *Gracilariopsis* spp. Seaweeds of the red order Gelidiales also produce agar. These include the agarweeds (*Gelidium* and *Pterocladia* spp.), which are commercially harvested, but for which aquaculture is not yet applied except at a research scale. All these seaweeds can be grown from cuttings, with this being the main method used for seed stock production for farms. Reproduction from spores or tissue culture is also possible, and is applied in some cases. Jellyweeds and Gracilariales are grown either at sea or in land-

[4] Standard aquatic plant names are used throughout this document for taxa where standard names have been assigned that differ from the scientific (genus) name. Other taxa are referred to using current scientific names following the World Register of Marine Species (WoRMS). Scientific names, following WoRMS, are also used when referring to specific taxa within groups that share the same standard name.

based ponds, tanks or raceways, while Irish moss is grown mainly in land-based systems, but occasionally at sea. Cuttings taken from one production cycle are normally used as seed stock for the subsequent cycle without separate hatchery or nursery cultivation. Hatchery cultivation is, however, used for production from spores or tissue culture.

Nori

Nori *(Porphyra* and *Pyropia* spp., order Bangiales) are red seaweeds grown predominantly for food. Nori species have a three-stage life cycle, with a microscopic shell-boring tetrasporophyte, known as the conchocelis, a macroscopic gametophyte, and a microscopic carposporophyte that grows on the gametophyte. Cultivation includes hatchery cultivation of the conchocelis stage, which is seeded onto shells and grown in tanks, ponds or raceways, followed by seeding of the gametophyte onto nets for out-planting at sea.

Asparagopsis and other species

Asparagopsis belong to the red seaweed order Bonnemaisoniales. Seaweeds of this order have a three-stage life history similar to that of nori, i.e., a free-living tetrasporophyte, a macroscopic gametophyte stage, and a carposporophyte stage that develops attached to the gametophyte. Unlike nori, however, the tetrasporophyte stage of *Asparagopsis* is filamentous and does not require a specific substrate for cultivation. Cultivation systems for *Asparagopsis* are being developed, and are likely to include hatchery cultivation and grow-out either at sea or in ponds, tanks or raceways.

Small-scale cultivation of other red seaweeds occurs globally, including of *Palmaria* spp. (order Palmariales), which are grown for food. *Palmaria* spp. are primarily vegetatively propagated and grown in tanks or ponds.

2.3 Green seaweeds

Cultivated green seaweeds, which are grown primarily for food or use in animal feeds, include sea lettuces (*Ulva* spp., order Ulvales) and sea grapes (*Caulerpa* spp., order Bryopsidales). Green seaweeds have either a single or a two-stage life history, but asexual reproduction is prevalent. In cultivation, green seaweeds are typically vegetatively propagated, and normally grown in tanks or ponds due their relatively delicate structure, although at-sea cultivation has been trialled in some areas.

2.4 Cultivation systems

Aquaculture cultivation systems, including those applied for seaweed, fall into two main categories: closed or semi-closed and open or semi-open. Closed systems are characterised by a high degree of control over the movement of water, stock and people, e.g., re-circulating aquaculture systems. Semi-closed systems allow for some control over water and generally high control over stock and people, e.g., onshore ponds, flow-through tank systems. Semi-open systems, e.g., at-sea cultivation, provide some control over stock (i.e., stock is attached to longlines or contained in mesh) but little to no control over water or people. Open systems are systems in which stock is not contained, e.g., if cultivated seaweeds are used for restoration or to replenish wild stocks.

3 Major pest and disease hazards

Major diseases of Australian seaweeds and key pests that will impact seaweed aquaculture are yet to be identified. Seaweed species cultivated in Australia are likely to be different to those cultivated elsewhere because most established cultivated species are not native to Australia, although close relatives of some occur.

Many seaweed pests and diseases, however, are not species-specific and can impact or infect multiple seaweed taxa, although the signs and severity of impacts may vary across taxa. The main types of pests and diseases that will impact the Australian seaweed are, therefore, likely to be similar to those that affect seaweed aquaculture operations elsewhere, even though the specific pathogens or pest species may vary. In a tailored, species-specific biosecurity plan, farms should seek up-to-date information and consider the most likely pest and disease hazards, i.e., those with potential adverse consequences for the taxon under consideration, as per the examples in Section 3.3. A template for recording relevant information on pest or disease hazards is provided in Table 5.

Table 5. Template for recording information on a pest or disease hazard.

[Name of pest or disease]	Description
Disease agent or pest	[Organism]
Distribution	[Endemic or exotic]
Consequences	[Reduced production, product value or mortality]
Transmission	[Direct, indirect or vectors]
Further information	[Manuals or websites]

Many diseases of seaweeds appear to be environmentally mediated, occurring only under suboptimal growth conditions or where seaweed tissue has been damaged, e.g., by grazers. The causative organisms for these diseases are opportunistic pathogens that are typically present but proliferate in diseased tissue. It is impractical to exclude all opportunistic pathogens from cultivation systems, and the maintenance of suitable growing conditions is imperative to prevent such diseases. Hazards posed by opportunistic pathogens should, however, be considered within biosecurity plans because basic hygiene measures can assist in preventing or limiting losses should an environmentally mediated disease occur. For example, because pathogens proliferate in diseased tissue, the isolation, or removal and appropriate disposal, of diseased specimens will lower pathogen loads and hence reduce the risk of the disease spreading to susceptible healthy stocks.

Knowledge of seaweed pests and diseases globally demonstrates that opportunistic bacteria, water moulds (oomycetes), parasitic epi-endophytes and macro-epiphytes are important seaweed pathogens, and are therefore likely to also affect Australian taxa. Protozoa, fungi and viruses are also potential disease agents. A summary of seaweed pests and diseases is provided below. Further detail can be found in the final report for the AgriFutures Australia project PRO-017299 *Biosecurity for the Australian seaweed industry*.

3.1 Seaweed diseases

Common signs of seaweed diseases caused by bacteria, fungi, protists and oomycetes include colour changes, particularly bleaching, and thallus decay, often beginning with small holes or lesions. Bleaching in seaweeds reflects a loss of photosynthetic pigments, leading to poorer photosynthetic performance and reduced growth. Bleaching is often also accompanied by, or progresses to, necrosis, with the loss of considerable cultivated biomass possible where tissue degrades at or near to the culture substrate (e.g., ropes or net), or where large-scale necrosis or thallus mortality results. Given the very similar signs and impacts of diseases caused by a range of pathogens, diagnosis of seaweed disease typically relies on microscopic examination and molecular investigation. It should be noted, however, that not all micro-organisms proliferating on diseased seaweeds are pathogenic.

Water moulds cause two major diseases impacting nori production: red rot and Olpidiopsis blight (Section 4.1.1.). The oomycete species causing Olpidiopsis blight can infect several other red seaweeds, although not all species develop clinical disease. These infections allow the pathogen to persist in the environment during breaks in nori production, and serve as a reservoir for re-infection. *Olpidiopsis* spp. also produce zoospores that remain infective for several days. The *Pythium* spp. causing red rot disease infects not only other seaweeds but also freshwater and terrestrial plants and algae, with river run-off a potential source of infection. *Pythium* spp. can also persist for long periods on decaying plant and algal material. Water moulds of the genus *Petersenia* cause disease in cultivated Irish moss and in *Palmaria* spp., with impacts including tissue necrosis and reduced growth.

Diseases caused by bacteria, fungi and protists have a major impact on production of carrageenophytes (including jellyweeds and Irish moss), Gracilariales (agar producers), and Laminariales (including kombu and wakame). In Laminariales, nursery production can be severely impacted. Bacterial bleaching diseases have also been characterised in wild seaweeds, including *Delisea pulchra*, a species from the same order (Bonnemaisoniales) as *Asparagopsis.*

Bacterial phyla Bacteroidota, Alphaproteobacteria and Gammaproteobacteria contain many species implicated as causative agents in seaweed diseases across many seaweed taxa, although not all representatives of these groups are pathogenic. Many bacteria demonstrated to be pathogenic by inoculation experiments are opportunistic and are common on healthy seaweeds, although they proliferate on diseased specimens. Fungi, including Ascomycota and Chytridiomycota, are also associated with seaweed disease in nori, jellyweeds and brown seaweeds, with chytrids also associated with disease in green seaweeds and wild stocks of several red seaweeds. As with bacteria, not all seaweed associated fungi are pathogenic. Endophytic amoebae are associated with disease in Gracilariales and Laminariales. A diverse range of viruses infect marine algae with important ecological effects, including the ability to lyse bloom-forming microalgae. Seaweed viruses are relatively poorly studied but are recognised as important disease agents in cultivated nori and have been implicated in die-backs of wild seaweed populations, including of golden kelp.

3.2 Epiphytes, culture contaminants and grazers

Several endophytic seaweeds, including the brown *Laminariocolax* and *Laminarionema* spp. (Ectocarpales) and the green *Ulvella* (formerly *Acrochaete*) spp. (Ulvales), are obligate or facultative parasites of seaweeds. A red seaweed *Vertebrata lanosa* (Ceramiales) is an obligate epiphyte of the brown seaweed *Ascophyllum nodosum.* Impacts of parasitic algae on cultivated seaweeds include lesions, frond holes, thallus deformation, reduced growth and reproductive output, and lower product value. Thallus deformations in cultivated brown seaweeds can also weaken their attachment to culture ropes, leading to significant biomass loss. Phytomyxea (kingdom Chromista, phylum Rhizaria) are microscopic obligate endoparasites that can also infect brown seaweeds and cause galls or other deformities, impacting product quality and increasing the likelihood of infection by some pathogens. Phytomyxea form resting cysts that may facilitate dispersal and re-infection.

Other, non-parasitic, epiphytes and contaminants impact seaweed cultivation through competing for space, light and nutrients, thereby reducing crop growth, and through contamination that reduces product value. The microscopic and seedling phases of many seaweeds are sensitive to contamination at the hatchery and early nursery stages. Microorganisms, including other algae, fungi, bacteria, cyanobacteria and micro zooplankton (primarily protozoans), can graze on or outcompete the macroalgal cultures.

Epiphytes affecting adult seaweeds include microscopic organisms, e.g., diatoms, cyanobacteria; other macroscopic seaweeds; and invertebrates. Diatoms are a noted problem for nori cultivation (see section 3.3). Epiphytic filamentous algae of the *Polysiphonia-Neosiphinia* group, now identified as *Melanothamnus* spp. (Ceramiales), are considered a serious pest of jellyweeds, causing thallus damage and deformations, reduced growth and carrageenan content, and promoting bacterial infections. Filamentous algae also cause issues for the production of Gracilariales. Epiphytic invertebrates impacting seaweed aquaculture of both red and brown seaweeds include fouling species such as hydroids, bryozoa and bivalves.

Grazers impacting seaweed production include herbivorous fish and a range of invertebrates, including gastropods and small crustacea such as caprellids, isopods and amphipods (mesograzers). Damage by grazers can range from small holes on seaweed blades, which may promote infection, to consumption of entire thalli. Small crustacea can burrow into and consequently destroy brown seaweed stipes with subsequent thallus detachment. Some grazers may, however, be beneficial by consuming and thereby limiting the growth of epiphytic seaweed.

3.3 Hazards for some cultivated seaweed species

Details of key pest and disease hazards impacting some of the main farmed seaweeds globally are included in this section, but **these details should not be considered complete**. These examples are given to provide information on these pests and diseases because Australian seaweed aquaculture will likely experience similar infections, although the specific pest or disease agent may vary. The examples also demonstrate the type of information that is important to capture about each hazard. In particular, the consequence and transmission routes of each hazard inform the risk assessment used to prioritise hazards for management (see Section 11). Understanding transmission routes also assists in determining which vectors should be prioritised for management and which mitigation measures (Section 6) will be most effective. More information on transmission routes is provided in Section 4.

Most seaweed diseases, even for many established cultivated species, are not well characterised, and not all transmission routes are well understood. Where data are lacking, it is important to take a precautionary approach and consider all potential transmission routes for the type of pathogen or organism(s) involved. New diseases emerge regularly in aquaculture, and with cultivation of novel seaweed species and establishment of seaweed farms in new areas, the likelihood new diseases will emerge is high. While specific measures cannot be applied to unknown diseases, generic biosecurity practices targeting key transmission routes can limit the likelihood of pest or pathogen entry and spread on your farm.

Hazards for nori

Table 6. Hazard information for green-spot disease.

Green-spot disease (GSD)	Description
Disease agent or pest	Chloroplast virus PyroV1
Distribution	Korea. Similar disease occurs in Japanese and Chinese nori production, and may also be caused by PyroV1 or a similar, related virus.
Consequences	Infected blades develop lesions and decay within 1-2 days. Disease can cause loss of 10-25% of the crop for a growing area. Severe outbreaks may cause complete loss of the crop for a growing season for many farms.
Transmission	Infected seaweed, contaminated water, contaminated equipment. Damaged blades more susceptible. Does not infect the sporophyte (conchocelis) phase.
Further information	Kim GH, Moon K-H, Kim J-Y, Shim J, Klochkova TA (2014) A revaluation of algal diseases in Korean *Pyropia* (*Porphyra*) sea farms and their economic impact. *Algae* 29, 249-265. Kim GH, Klochkova TA, Lee DJ, Im SH (2016) Chloroplast virus causes green-spot disease in cultivated *Pyropia* of Korea. *Algal Research* 17, 293-299.

Table 7. Hazard information for red-rot disease.

Red-rot disease	Description
Disease agent or pest	*Pythium porphyrae*, *Pythium pyropiae*, oomycetes. *Alternaria*, a fungus, may induce similar disease.
Distribution	Known from nori farms in China, Japan and Korea, isolated from wild nori in the Netherlands and New Zealand. Likely widespread globally.
Consequences	Infected blades decay within three days, may cause crop losses of up to 20% within an area and complete loss of a production cycle for individual farms.
Transmission	Infected seaweeds, *Pythium* zoospores may spread in water or on equipment. Infects red seaweeds across many taxa, plus freshwater and terrestrial plants and algae. River run-off may carry infections.
Further information	Kim GH, Moon K-H, Kim J-Y, Shim J, Klochkova TA (2014) A revaluation of algal diseases in Korean *Pyropia* (*Porphyra*) sea farms and their economic impact. *Algae* 29, 249-265. Diehl N, Kim GH, Zuccarello GC (2017) A pathogen of New Zealand *Pyropia plicata* (Bangiales, Rhodophyta), *Pythium porphyrae* (Oomycota). *Algae* 32, 29-39. Spencer MA (2004) *Pythium porphyrae*. In: Descriptions of Fungi and Bacteria, CAB International, 162, 1617. https://doi.org/10.1079/DFB/20056401617 Mo Z, Li S, Kong F, Tang X, Mao Y (2015) Characterization of a novel fungal disease that infects the gametophyte of *Pyropia yezoensis* (Bangiales, Rhodophyta). *Journal of Applied Phycology* 28, 395-404.

Table 8. Hazard information for Olpidiopsis blight

Olpidiopsis blight	Description
Disease agent or pest	*Olpidiopsis* spp. (*O. porphyrae*, *O. pyropiae*), oomycetes
Distribution	Known from nori farms in China, Japan and Korea, and wild nori and other Bangiales in Scotland.
Consequences	Tissue bleaching and decay. May causes losses of up to 25% of stock or production delays, or require early harvest to prevent spread.
Transmission	Infected seaweeds, zoospores may spread in water or on equipment. *Pontisma* spp. that cause disease in nori also infect other red seaweeds.
Further information	Kim GH, Moon K-H, Kim J-Y, Shim J, Klochkova TA (2014) A revaluation of algal diseases in Korean *Pyropia* (*Porphyra*) sea farms and their economic impact. *Algae* 29, 249-265. Klochkova TA, Shim JB, Hwang MS, Kim GH (2011) Host–parasite interactions and host species susceptibility of the marine oomycete parasite, *Olpidiopsis* sp., from Korea that infects red algae. *Journal of Applied Phycology* 24, 135-144. Badis Y, Klochkova TA, Brakel J, Arce P, Ostrowski M, Tringe SG, Kim GH, Gachon CMM (2019) Hidden diversity in the oomycete genus *Olpidiopsis* is a potential hazard to red algal cultivation and conservation worldwide. *European Journal of Phycology* 55, 162-171. Zuccarello GC, Gachon CMM, Badis Y, Murúa P, Garvetto A, Kim GH (2024) Holocarpic oomycete parasites of red algae are not *Olpidiopsis*, but neither are they all *Pontisma* or *Sirolpidium* (Oomycota). *Algae* 39, 43-50.

Table 9. Hazard information for diatom felt

Diatom felt	Description
Disease agent or pest	Epiphytic pennate diatoms, including *Navicula* and *Licmophora* spp.
Distribution	Known from nori farms in Korea. Diatoms are ubiquitous in the marine environment.
Consequences	Reduced crop growth, poorer crop quality and lower crop value, increased processing time and cost.
Transmission	Infected seaweeds, contaminated water or equipment.
Further information	Kim GH, Moon K-H, Kim J-Y, Shim J, Klochkova TA (2014) A revaluation of algal diseases in Korean *Pyropia* (*Porphyra*) sea farms and their economic impact. *Algae* 29, 249-265.

Hazards for jellyweeds

Table 10. Hazard information for epiphytic filamentous algae.

Epiphytic filamentous algae (EFA)	Description
Disease agent or pest	Red seaweeds, predominantly *Melanothamnus* (formerly *Neosiphonia*) and *Polysiphonia* spp. (order Ceramiales).
Distribution	Common in all areas with jellyweed cultivation. *Melanothamnus* and *Polysiphonia* spp. are widespread globally.
Consequences	Reduce growth of affected jellyweed and damage that increases the risk of disease from opportunistic pathogens. Lower crop value due to lower carrageenan yield and contamination.
Transmission	Infected seaweed, contaminated water, contaminated equipment.
Further information	Sugumaran R, Padam BS, Yong WTL, Saallah S, Ahmed K, Yusof NA (2022) A retrospective review of global commercial seaweed production – current challenges, biosecurity and mitigation measures and prospects. *International Journal of Environmental Research and Public Health* 19, 7087. Faisan JP, Luhan MRJ, Sibonga RC, Mateo JP, Ferriols VMEN, Brakel J, Ward GM, Ross S, Bass D, Stentiford GD, Brodie J, Hurtado AQ (2021) Preliminary survey of pests and diseases of eucheumatoid seaweed farms in the Philippines. *Journal of Applied Phycology* 33, 2391-2405.

Table 11. Hazard information for ice-ice disease.

Ice-ice disease (IID)	Description
Disease agent or pest	Pathogenic strains of *Vibrio*, *Alteromonas*, *Flavobacterium* or *Cytophaga* spp. (bacteria). Other bacteria and fungi may also cause IID. Environmental conditions or damage by epiphytes or grazers contribute to outbreaks.
Distribution	Common in all areas with jellyweed cultivation.
Consequences	Affected areas bleach and soften. Infected sections or whole thalli may decay and detach from cultivation lines. Loss of entire crop cycles possible in severe outbreaks.
Transmission	Infected seaweed (cultivated or wild), other transmission routes possible (e.g., water, equipment). Husbandry important.
Further information	Sugumaran R, Padam BS, Yong WTL, Saallah S, Ahmed K, Yusof NA (2022) A retrospective review of global commercial seaweed production – current challenges, biosecurity and mitigation measures and prospects. *International Journal of Environmental Research and Public Health* 19, 7087. Faisan JP, Luhan MRJ, Sibonga RC, Mateo JP, Ferriols VMEN, Brakel J, Ward GM, Ross S, Bass D, Stentiford GD, Brodie J, Hurtado AQ (2021) Preliminary survey of pests and diseases of eucheumatoid seaweed farms in the Philippines. *Journal of Applied Phycology* 33, 2391-2405.

Table 12. Hazard information for epiphytic seaweed.

Epiphytic seaweed	Description
Disease agent or pest	Seaweeds including red (e.g., *Laurencia* spp.), brown (e.g., *Sargassum* spp.) and green (e.g., *Ulva* spp.).
Distribution	Common in all areas with jellyweed cultivation. Also impact production of Gracilariales. Epiphytic seaweeds with potential to become pests are common globally.
Consequences	Reduced growth due to shading and competition, increased processing time, lower crop value.
Transmission	Pest seaweed propagules in water, on equipment or on other seaweeds.
Further information	Sugumaran R, Padam BS, Yong WTL, Saallah S, Ahmed K, Yusof NA (2022) A retrospective review of global commercial seaweed production – current challenges, biosecurity and mitigation measures and prospects. *International Journal of Environmental Research and Public Health* 19, 7087. Faisan JP, Luhan MRJ, Sibonga RC, Mateo JP, Ferriols VMEN, Brakel J, Ward GM, Ross S, Bass D, Stentiford GD, Brodie J, Hurtado AQ (2021) Preliminary survey of pests and diseases of eucheumatoid seaweed farms in the Philippines. *Journal of Applied Phycology* 33, 2391-2405.

Hazards for kombu and wakame

Table 13. Hazard information for green-rot ('falling off') disease.

Green-rot disease	Description
Disease agent or pest	Opportunistic alginic acid decomposing and sulphate-reducing bacteria. Environmental stressors may trigger disease outbreaks and proliferation of pathogenic strains.
Distribution	Recorded in kombu cultivation in China and the United States.
Consequences	Affects nursery stages particularly and may cause loss of an entire production cycle. Stipe and/or holdfast of the sporophyte becomes soft and decays, leading to loss of sporeling from the cultivation rope.
Transmission	Infected seaweed, contaminated water, contaminated equipment. Husbandry important.
Further information	Wang G, Lu B, Shuai L, Li D, Zhang R (2014) Microbial diseases of nursery and field-cultivated *Saccharina japonica* (Phaeophyta) in China. *Algological Studies* 145-146, 39-51. Li J, Pang S, Shan T, Su L (2020) Changes of microbial community structures associated with seedlings of *Saccharina japonica* at early stage of outbreak of green rotten disease. *Journal of Applied Phycology* 32, 1323-1327. Yarish C, Kim JK, Lindell S, Kite-Powell H (2017) *Developing an environmentally and economically sustainable sugar kelp aquaculture industry in southern New England: from seed to market*. University of Connecticut. https://digitalcommons.lib.uconn.edu/eeb_articles/38/

Table 14. Hazard information for brown endophyte diseases.

Brown endophytes	Description
Disease agent or pest	Ectocarpic algae: *Laminariocolax*, *Laminarionema* and others.
Distribution	Common in all areas with kombu cultivation and in wild Laminariales.
Consequences	Thallus deformations, lower crop value and increased risk of thallus loss from culture ropes.
Transmission	Zoospores in water, on equipment or on other seaweeds. Young sporelings are most susceptible to infection.
Further information	Bernard M (2018) Seaweed diseases and pests. Wageningen Marine Research. https://research.wur.nl/en/publications/seaweed-diseases-and-pests Bernard M, Rousvoal S, Jacquemin B, Ballenghien M, Peters AF, Leblanc C (2018) qPCR-based relative quantification of the brown algal endophyte *Laminarionema elsbetiae* in *Saccharina latissima*: variation and dynamics of host-endophyte interactions. *Journal of Applied Phycology* 30, 2901-2911. Murúa P, Patiño DJ, Leiva FP, Muñoz L, Müller DG, Küpper FC, Westermeier R, Peters AF (2019) Gall disease in the alginophyte *Lessonia berteroana*: A pathogenic interaction linked with host adulthood in a seasonal-dependant manner. *Algal Research* 39.

Table 15. Hazard information for epiphytic invertebrates (biofouling).

Epiphytic invertebrates	Description
Disease agent or pest	Bryozoans (e.g., *Membranipora* spp.,), mussels (e.g., *Mytilus* spp.), hydroids, ascidians and polychaetes.
Distribution	Common in all areas with kombu cultivation. Invertebrates with potential to become pests are common globally.
Consequences	Reduced growth due to shading and competition, increased processing time, lower crop value.
Transmission	Pest propagules in water, on equipment or on other seaweeds.
Further information	Stévant P, Rebours C, Chapman A (2017) Seaweed aquaculture in Norway: recent industrial developments and future perspectives. *Aquaculture International* 25, 1373-1390. Kim J-O, Kim W-S, Jeong H-N, Choi S-J, Seo J-S, Park M-A, Oh M-J (2017) A survey of epiphytic organisms in cultured kelp *Saccharina japonica* in Korea. *Fisheries and Aquatic Sciences* 20, 1.

Table 16. Hazard information for amphipod grazing.

Amphipod grazing	Description
Disease agent or pest	*Ceinina japonica*, a gammarid amphipod.
Distribution	Affects wakame in Korea.
Consequences	Bores into stipe or midrib, sometimes causing thallus separation and loss from cultivation lines. Damaged areas susceptible to infection.
Transmission	Infected seaweed, equipment.
Further information	Neill K, Heesch S, Nelson W (2008) *Diseases, pathogens and parasites of Undaria pinnatifida*. MAF Biosecurity New Zealand Technical Paper No: 2009/44. National Institute of Water and Atmospheric Research.

4 Major routes for disease transmission and pest introduction

Pests and pathogens can enter and exit your farm via many routes. These routes need to be considered to manage the risk of pests or pathogens entering your farm, diseases spreading or pests proliferating within your farm, and pests or diseases leaving your farm.

For diseases, pathways that place high loads of viable pathogens in close contact with a susceptible host are most likely to result in infectious disease. These pathways need to be identified and addressed as a priority. The main routes of transmission include stock, water, equipment, people, farm inputs (e.g., nutrients and other additives) and waste. Wild animals may also introduce pathogens.

4.1 Transmission routes onto the farm

Transmission routes onto a farm are managed by entry biosecurity measures.

Stock

Seaweed entering the farm can present a significant biosecurity risk, particularly if it is of unknown health status or from a location with known or potential IAS occurrence. Seaweed vectors of pests and disease can include brood stock,[5] seed stock, genetic material (e.g., spores, protoplasts, gametophyte cultures) and seaweed products (e.g., those harvested at other sites). IAS may occur as epiphytes on seaweeds. Wild seaweeds that occur in the vicinity of farms or water intakes can also present a risk of disease transmission or pest introduction to the farm.

People

People can present a significant risk of disease introduction, particularly where they visit other farms or environments containing pests or diseases of concern. People can include staff, contractors, visitors and unauthorised entrants. They can introduce pathogens, microscopic pests or pest propagules via contaminated skin, clothing and footwear.

Equipment, vehicles and vessels

Equipment that has been in contact with aquatic environments and particularly with seaweeds can transmit diseases or introduce pests to the farm. Equipment can include anything brought onto the farm, such as harvest, cultivation, transport and diving equipment. The level of risk will depend on the history of use, e.g., equipment used at other farms or re-used on the farm (e.g., for harvest or processing) will have a much higher risk compared with new equipment.

Vehicles such as cars, trucks and tractors can bring pathogens, pests, IAS or pest/IAS propagules onto the farm. As with equipment, the level of risk will depend on the history of use.

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[5] For seaweeds, brood stock would include material kept specifically to produce spores/gametes or cuttings for cultivation. Not all seaweed cultivation will involve brood stock, however, given that seed stock may be obtained from cuttings taken from previous cultivation cycles, sporulation of cultivated or wild-collected material that is not maintained as brood stock, via tissue culture, or from seed banks (e.g., gametophyte cultures).

Vessels are a likely way pests or disease can be introduced to a farm, particularly when they have been used at other farms or have been in close contact with seaweeds (e.g., boats used for harvest or collection of wild material for brood stock or spore production). IAS may grow on vessel hulls and cultivation equipment, and IAS or their propagules may also be carried on other equipment.

Water

A farm's water supply is an important asset that has a major influence on seaweed health. In semi-open systems, such as sea-based farms, there can be little control of water as a route of disease transmission; however, the nature of water currents and positioning of farms and cultivation units within farms can be considered in managing biosecurity. For land-based facilities, disease transmission risks will depend on the nature of the water source, the presence of wild seaweeds in that water source, and the proximity of other farms that may discharge into the water source. Water used as the transport medium for stock may also carry pathogens, pests, or pest and IAS propagules.

Nutrients and other farm inputs

The risk of disease transmission from inorganic nutrients will depend on the sterility of the solution. Microscopic contaminants may proliferate in nutrient solutions that are not sterile. Organic additives, including extracts from other seaweeds, may also pose a risk, depending on the method of extraction and the nature of the medium used. Infrastructure and equipment used to prepare, store or deliver nutrients may also house and spread pathogens and microscopic contaminants.

Waste

Waste products, such as diseased stock, contaminants and epiphytes removed from cultivation systems, processing water, processing waste and cleaning effluent, can be vectors for transmission of diseases or pests onto a farm. Appropriate infrastructure and procedures are required to manage the biosecurity risks associated with these waste products.

Animals

Animals entering the farm, including birds and fish, plus vermin for land-based facilities, may also carry diseases or pest propagules.

4.2 Transmission routes within the farm

Transmission routes within a farm are managed by internal biosecurity measures.

The routes of transmission within your farm are similar to those onto your farm. However, the transmission risk is for the spread of pests or diseases between different production and processing areas. In many cases, different farm populations will have different health status. For example, hatcheries may have the highest health status; nursery areas may have a slightly lower health status; and grow-out populations may have the lowest health status. Consideration should be given to the risks of pest or disease transmission between areas with different health status.

To mitigate the impact of a pest or disease outbreak, the risk of transmission between production areas should be considered. For example, different grow-out areas can be managed separately to prevent an outbreak in one area spreading to all grow-out areas.

4.3 Transmission routes from the farm

Transmission routes from a farm are managed by exit biosecurity measures.

The pest and disease transmission routes from your farm are similar to those onto your farm. Pest, IAS or disease transmission from the farm can impact farm water sources, neighbouring farms, native or feral seaweed populations, and other habitats adjacent to the farm. If pests or diseases become established or proliferate in adjacent seaweed populations, they can pose an ongoing threat to your farm and the environment. This is particularly the case where the farm is an open or semi-open system with limited scope for physical separation from adjacent aquatic environments.

Aquaculture licence conditions typically require that farms do not adversely impact surrounding environments, including through stock 'escapes' or releases. For seaweeds, 'escapes' could include farmed stock spawning or the release of vegetative fragments for seaweeds able to reproduce clonally. The release of farmed stock can result in farmed cultivars establishing and either outcompeting or hybridising with wild stocks, with the latter leading to potential genetic impoverishment or other impacts. In several jurisdictions, aquaculture operators also are subject to legislated general biosecurity obligations, including preventing the introduction or spread of IAS. Exit biosecurity measures will address licence requirements and general biosecurity obligations in addition to ensuring the sustainability of the aquaculture operation.

Part 2 What to include in your biosecurity plan

This part of the document provides guidelines for development of a biosecurity plan on your farm. The rationale for the guidelines is provided in explanatory text. These guidelines can be used in conjunction with the biosecurity plan template in Part 5 to develop your farm biosecurity plan. Not all components listed in these guidelines will be required for all biosecurity plans. The components to include in your biosecurity plan, and the level of detail required, will depend on the nature of the enterprise, and be informed by a risk assessment (Section 11).

5 Farm information

The design of your farm and the availability of infrastructure will determine how biosecurity can be managed. This section describes what information should be considered as you develop your biosecurity plan. Changes to the farm should be considered in the context of the biosecurity plan.

5.1 Production details

Summarise all relevant elements of your enterprise, including, as appropriate:

- the type of enterprise (e.g., grow-out enterprise or hatchery);
- the cultivated species and life stage(s);
- the licensed maximum farm biomass;
- annual production outputs;
- the origin of brood stock and/or seed stock (source location and date introduced to the farm);
- production and administrative activities;
- staff details, including the number, their positions and their areas of responsibility;
- any sites associated with the cultivation sites, such as separate vessel/equipment storage sites, processing sites or offices;
- the proximity to other biosecurity risks (e.g., other farms, processors);
- chemical use, including fertiliser, growth promotors, water treatment etc.

5.2 Site location and features

Include a map of the farm that shows major facilities (e.g., buildings, roads, ponds, water intake and discharge) and significant natural features of the site (e.g., creeks and coastline). For sea-based farms, include coordinates of the entire lease area and production sites within the lease area (e.g., where moorings are located). Maps of sea-based farms should also include the locations of neighbouring farms, relevant wild seaweed stocks, marinas and boat ramps.

Layout of the facility

For land-based farms, provide a diagram of the facility (e.g., engineering/building plans). Include each building and each system, entry and exit points, and major flow patterns (stock movement, employee and visitor movement). Identify the life stages (e.g., gametophytes, nursery, mature) found in each system.

For sea-based farms, provide a detailed layout of production sites within the lease area, including information on the specific cultivation systems and stock for each site, and patterns of water movement (e.g., tidal flow). Also include diagrams of any relevant land-based facilities, such as vessel storage and processing facilities.

The diagram should contain the following (as applicable):

- site access points;
- vehicle parking areas;
- reception points for visitors and contractors;
- water supply, treatment and discharge routes;
- water pumps and valves;
- water intake and discharge points;
- equipment and vehicle wash-down areas;
- equipment and vehicle storage areas'
- production areas within the facility (e.g., hatchery, nursery and grow-out);
- quarantine facilities within the farm;
- location of footbaths and disinfection areas;
- measures to prevent the release of pests and farmed stock (e.g., screens on discharge water);
- any features important for the species being farmed;
- typical stock movements through the facility (e.g., from hatchery to nursery);
- waste disposal areas;
- site security (include the locations of lockable doors and gates).

Biosecurity zoning

Overlay biosecurity zones on a map of your enterprise. These zones will need to be described in detail within your plan and supported with standard operating procedures (SOPs; see Section 12). The biosecurity zones will represent areas that are both physically and functionally separate, so you should be able to define the location and the type(s) of biosecurity measure(s) separating those areas.

In semi-open systems, production areas may be considered as separate biosecurity zones where the distance between the areas, accounting for hydrodynamics and characteristics of relevant hazards, is adequate to make the likelihood of pest or disease transmission remote or unlikely (see Section 11 for the definition of likelihood categories).

Pertinent characteristics of pest and disease hazards include the ability to be transmitted with water movement and the duration that the pest propagules or pathogens remain viable or infective after release. Where pest or disease transmission is feasible (likelihood of possible or greater), production areas should be considered and managed as a single zone.

Separate zones should have infrastructure and/or sanitary protocols to prevent the transfer of disease from one area to another with movement of water, people, stock, equipment and vehicles. Where possible, separate equipment should be used in each zone, and dedicated staff used for sensitive zones. Note that sensitive zones may include zones with high-health-status stock that poses a lesser likelihood of disease transmission but is at high risk of infection, e.g., the hatchery, and zones with stocks of unknown or low health status, e.g., wild-collected brood stock, that have a greater likelihood of carrying pests or disease and hence may pose a high risk of transferring pests or disease to other stock.

Where people, equipment or vehicles must move between zones, it is important to prioritise and manage movement to minimise pest or disease transmission risks. Movements should be ordered from zones with stock that has the highest health status to zones with stock that has the lowest health status, while considering the specific hazards and risk profile of each zone and activity. Should movements be required that present a potential risk of pest or disease spread, ensure a risk assessment (see Section 11) is prepared to justify the activity.

5.3 Key contact details

Document key details for internal and external contacts relevant to the operation's management, biosecurity and stock health. Relevant contacts may include:

- company, farm, and specific area managers (e.g., biosecurity or seaweed health manager, hatchery manager);
- consulting seaweed health professionals;
- diagnostic laboratories;
- state/territory government biosecurity, aquaculture and environmental protection authorities
- local government/council;
- port authority, marina managers;
- emergency services;
- any relevant industry representatives (e.g., other nearby aquaculture businesses, peak industry body executive officers and/or association representatives).

6 Protocols to address potential hazards

This section outlines risk management measures to address potential pest and disease hazards for seaweeds (Section 3), considering the major transmission routes (Section 4) common to the range of cultivation systems (closed, semi-closed, semi-open, open) that may be used.

Not all mitigation measures will be practical or suitable for all systems; options will be particularly limited for semi-open and open systems. Similarly, not all potential hazards will be relevant for all operations, e.g., not all operations will use divers. In developing biosecurity plans, farms will need to consider the practicality of mitigation measures for their specific hazards (as prioritised by a risk assessment), cultivation systems, farm layout and farmed species. Protocols outlined in this section are general measures for mitigating pest and disease risks. As additional knowledge of seaweed pests and diseases is obtained, measures for mitigating specific pest or disease risks are likely to be developed and should be implemented where relevant.

Within this section, management measures are shown for routine mitigation (i.e., for any case where the assessed risk is not negligible) and for additional mitigation (i.e., in the case of high or extreme assessed risk). This reflects that cases regarded as having higher risk will typically require more stringent mitigation measures to be implemented than cases regarded as having medium or low risk. The mitigation measures for high and extreme-risk cases should be considered additional to the measures applied for low- and medium-risk cases, except where the mitigation action is one performed instead (e.g., preventing movement instead of implementing decontamination). Where the assessed risk is low or negligible, mitigation measures are not essential, but it is always prudent to apply mitigation measures wherever practical to protect against unknown hazards.

6.1 General property management

Objective: Manage the risk of people, stock and equipment transmitting pathogens onto, within and from the farm.

Effective property management is necessary to manage disease transmission routes so that effective controls can be established. For example, perimeter fencing, designated entry and exit points, and signage can be used to direct visitors and contractors to control points (e.g., reception) where biosecurity risks can be assessed (e.g., assessing the risk presented by a visitor) and any measures applied (e.g., disinfection of equipment).

Table 17. Guidelines for property management to mitigate the risk of pest or pathogen transmission.

Routine measures	
G1.	Land-based farms should have a secure perimeter fence or otherwise well-defined boundary, establishing a clearly defined biosecurity zone. Entrances to the property should be able to restrict vehicle and foot traffic, and should be locked during non-visitor hours.
G2.	Production units (e.g., sheds, ponds, tanks, raceways, longlines) should have a unique and permanent identifier.
G3.	Farm maps and diagrams showing relevant biosecurity zones should be available (see Section 5).
G4.	Relevant information for key internal and external contacts should be readily available (see Section 5).

6.2 People

Objective: Manage the risk of people transmitting pathogens onto, within and from the farm.

The movement of people (including staff, contractors and visitors) onto and within the farm should be controlled to manage the risk of disease entry into the farm, spread within the farm, and spread from the farm. Unauthorised entry should be managed through appropriate property management measures.

Table 18. Guidelines to manage the risk of people transmitting pests or pathogens.

Routine measures
G5. Staff and visitor access should be managed (through access controls and signage), and the risk they present should be assessed.
G6. The farm biosecurity rules should be explained to all visitors.
G7. Measures to prevent disease entry should be applied to all persons entering and exiting the farm (e.g., dedicated changing areas, farm footwear and handwashing facilities), and, if assessed as necessary, to persons moving between different production areas within the farm. For high or extreme-risk cases, see G15 and G16.
G8. Production units should be managed separately to reduce the risk of disease spread within the farm. Staff should be assigned to production units based on risk.
G9. Staff should wear freshly laundered clothes daily and change into designated farm-only footwear on entry.
G10. Staff should record overseas travel and declare contact with other aquaculture facilities.
G11. Staff should receive annual training in pest and disease identification, and the steps involved in recording, reporting and investigating disease events.
G12. Divers should disinfect all equipment between visiting different leases or areas with stock from different cultivation cycles.
Additional measures for high and extreme-risk cases
G13. Access to sensitive areas (e.g., hatcheries, quarantine areas) should be restricted to dedicated, authorised staff only.
G14. If staff must work in multiple production units or zones, movements should be ordered from zones with the highest health status stock (i.e., with lesser likelihood of having a pest or disease) to the lowest health status stock (i.e., with greater or unknown likelihood of having a pest or disease), while considering the specific hazards and risk profile of each zone and activity. Appropriate decontamination procedures should be applied if movements assessed as high risk are unavoidable.
G15. Visitors should complete a biosecurity declaration on arrival to ensure their risk to hatchery biosecurity can be assessed. Consider refusing entry to high-risk visitors.
G16. Visits should be unidirectional (as per G14). Visitors should be accompanied by a staff member at all times.
G17. Records of staff and visitor movements should be kept.
G18. Staff should be prohibited from visiting other seaweed aquaculture sites or undertaking activities (including recreationally) that carry a risk of contact with relevant wild seaweeds before entering the farm (unless they have followed your SOPs to mitigate disease risks, including appropriate decontamination where required).
G19. Staff and visitors should be prohibited from bringing uncooked seafood products or bait to the workplace.

Staff training

Objective: Ensure all farm staff understand their responsibilities in maintaining farm biosecurity.

It is important that farm staff clearly understand their responsibilities in maintaining farm biosecurity. Staff should be able to recognise signs of ill health and any pests of concern in seaweeds; be aware of the major routes of pest and disease transmission onto, within and from the farm; understand the farm biosecurity plan and their responsibilities for its implementation; and be familiar with work practices and SOPs that support the farm biosecurity plan. Arrangements for delivering biosecurity training for staff should be in place. Participation in training should be documented, and learning evaluated. Training should cover emergency procedures.

Table 19. Guidelines for staff training.

Routine measures
G20. A staff member should be made responsible for overseeing farm biosecurity.
G21. Staff should understand the disease risks to the farm, the role of the farm biosecurity plan in managing disease risks, and their responsibilities for its implementation, including response protocols.
G22. Staff should receive training on the aspects of the farm biosecurity plan relevant to their work, and have access to the farm biosecurity plan and supporting procedures.

6.3 Stock

Objective: Manage the risk of stock transmitting pathogens onto, within and from the farm.

Farmed stock

The pest and disease risks associated with intentional introduction of brood stock, seed stock and genetic material (e.g., spores, microscopic life stages, spore-producing tissue) to the farm should be assessed prior to their introduction. Appropriate measures should be implemented to manage identified risks. There may be government requirements to address the disease, pest and IAS risks associated with intrastate or interstate movement of seaweeds for aquaculture. State or territory authorities in the receiving jurisdiction should be contacted to determine requirements.

Obtaining healthy stock is critical. For clonally propagated seaweeds, cuttings from each cultivation cycle are often used as seed stock for the next cycle, allowing propagation of desirable phenotypes (e.g., faster growing, higher survival). Selected cuttings should be carefully inspected under magnification for signs of pests and diseases, such as discolouration, wounds and the presence of epiphytes. Washing and mild chemical treatments may be effective in removing or inactivating some pests and diseases, but are unlikely to prevent all problems, particularly endophytes.

To produce seed stock via sporulation, sexual reproduction or micropropagation, source material should similarly be selected to be as clean and healthy as possible. The introduction of seed stock of new species or strains can improve crop vigour, but the risks of new stock introducing pests and diseases need to be considered. Fertile tissue sections used for spore or gamete production can be subject to stronger decontamination procedures than would be applied to whole thalli because these procedures typically result in physiological damage to the treated tissue but do not impair spore or gamete performance. Tissue used for spore production or micropropagation should be processed away from the nursery area to prevent cross-contamination, and appropriate equipment (e.g., disposable gloves) used during preparation. Following spore release or explant production, remaining material should be disposed of appropriately.

For the establishment of new aquaculture species and potentially enterprises in new areas, brood stock or material for spore production will initially be wild-collected. Wild-collected material should be carefully selected but will still be typically higher-risk than other brood stock.

Quarantine procedures should be considered where pest or disease risks are high, and permanent quarantine may be appropriate for wild-collected brood stock. Testing protocols for specific diseases of Australian seaweeds will need to be developed once diseases of concern have been identified. Up-to-date information should be sought, and relevant experts consulted to determine the most appropriate testing and/or quarantine protocols to apply.

Table 20. Guidelines to manage the risk of pest or pathogen transmission by intentional stock movements.

Routine measures
G23. The health of all stock introduced to the farm should be assessed, and records of the source and the date of introduction of all stock kept. Translocation approvals or permits must be obtained if required by the receiving state or territory authority. See G34 for cases of higher risk.
G24. Movement of stock between different farm populations should only occur after the disease risks have been considered, and with a view to maintaining high health status stock.
G25. Movement records should be maintained for all stock moved onto the farm, between zones of different biosecurity status within the farm, and from the farm.
G26. Stock management activities, including harvest, cleaning and adding treatments, should be recorded.
G27. Stock used for out-planting to semi-open (e.g., at-sea cultivation) or open (e.g., to replenish or restore wild stocks) systems should be of high health status.
G28. Stock health should be inspected regularly[6] and observations should be recorded. Health monitoring records should be kept for different stock populations within the farm, and should include details of any disease signs, mortality, treatments, disease testing and relevant environmental information.
G29. Health problems should be investigated with the assistance of relevant experts where needed. The farm should have the capability to rapidly collect and preserve samples for investigations.
G30. Stock showing signs of disease or pest infection should be isolated until the cause is known and the situation is resolved.
G31. Stock stress should be minimised by ensuring appropriate water quality, lighting, stocking density, fertilisation and handling.
G32. Different stock (e.g., stock from different cultivation cycles) should be maintained in separate areas (land-based) or leases (sea-based).
G33. Fallowing periods or crop rotation should be implemented.
Additional measures for high and extreme-risk cases
G34. Stock being introduced to the farm should have a known health status that is equal or better than stock already on the farm.
G35. If the health status of stock being introduced to the farm is unknown (e.g., wild brood stock or seed stock of unknown health status), the material should be isolated from other farm populations in separate production units or dedicated quarantine facilities.
G36. Quarantine of high-risk brood stock should be lifelong with a view to producing high-health or specific-pathogen-free progeny that would become brood stock.
G37. Where feasible, quarantined stock should be treated to mitigate disease risks. Treatments must be conducted in accordance with legislative and regulatory requirements.
G38. Diseased stock that is not able to be isolated, and any material showing signs of severe disease (e.g., necrotic tissue), should be removed from production units/leases as soon as possible.
G39. Stock removed from cultivation should be managed to minimise risk to other farmed and wild stocks. Where removed stock must be disposed, appropriate disposal methods[7] should be used; do not return removed stock to the environment.
G40. The farm should have equipment and contingency plans to manage diseases and to accommodate emergency harvest or disposal of large stock volumes (e.g., capacity to store and process high volumes of harvested stock or pre-arranged high-volume disposal sites and methods). Alternative uses for stock, e.g., in composts, may be considered where the risks of use are acceptable.

[6] The appropriate frequency will depend on the cultivation system and the assessed risk. Daily observations are appropriate for land-based operations, but for sea-based cultivation, weekly or monthly inspections may be appropriate. Observations should be made more frequently where the assessed risk is higher.

[7] Infected stock removed from cultivation may still be suitable for use, hence disposal may not be required. Measures should be in place, however, to ensure infected stock that has been harvested does not pose a risk to other stocks.

Unintentional stock releases, wild stocks, and animals

The pest and disease risks associated with wild seaweed stocks and animals need to be assessed, including risks of disease transmission from wild stocks or by animals, from the introduction of epiphytes or grazers, and from the escape of farmed material. Appropriate and effective measures should be implemented to manage the identified risks.

In closed (e.g., recirculation systems) and semi-closed (e.g., onshore ponds and flow through tanks) facilities, risks can often be managed through physical means, such as screens and filtration. Filtration to approximately 0.2 µm or potentially finer may be required to prevent the entry or exit of some pest propagules, or the release of propagules from farmed stock. Additional measures used to treat water (see Section 6.5) may also be required.

In semi-open systems (e.g., longlines), there is less opportunity to manage interactions with wild populations; however, it may be possible to reduce interactions (e.g., by minimising the risk that farmed seaweeds will spawn or produce vegetative fragments that may establish populations nearby). This may be done through selecting appropriate stock (e.g., local, genetically diverse cultivars or sterile strains) and cultivation period (e.g., harvesting prior to stock becoming fertile), avoiding sites in close proximity to wild seaweeds, and using appropriate infrastructure (e.g., containment of cultivated seaweeds in suitable mesh, and using moorings and longlines robust to local conditions). Choosing an appropriate cultivation period can assist in avoiding epiphyte overgrowth. Cultivating seaweed at an appropriate density can also assist in preventing epiphyte proliferation. Seaweed planting should be dense enough to allow the cultivated crop to outcompete fouling seaweeds or invertebrates, but not so dense as to result in self-shading and competition. It should be noted that dense planting can also promote more rapid disease progression should an outbreak occur. Farm managers should therefore investigate the most suitable planting density for their situation.

In addition to grazing pests, other aquatic and potentially non-aquatic animals may act as vectors for transmission of aquatic diseases or IAS onto, within and from the farm. These animals may include herbivorous or scavenging animals, such as fish, birds or (for land-based farms) rodents. Consideration should be given to controlling these animal populations (e.g., rodents) or preventing their movement onto or within the farm (e.g., netting to exclude birds from ponds). Netting may be used to prevent damage from herbivorous fish during at-sea cultivation, but physical exclusion of mesograzers such as small crustacea is likely to be infeasible.

Table 21. Guidelines to manage the risk of pest or pathogen transmission by unintentional stock movements, wild stocks and animals.

Routine measures
G41. In semi-closed systems, intakes should be positioned away from wild seaweed stocks and entry of aquatic animals (especially mesograzers), and pest propagules in the water supply should be prevented (see also Section 6.4).
G42. In semi-open systems, locations should be considered with respect to wild seaweeds and options to limit access by herbivorous fish to production units.
G43. For at-sea cultivation, systems should be used that are suitably robust for the conditions, and infrastructure should be regularly inspected.
G44. Genetically diverse local cultivars or appropriate disease-resistant strains should be used (refer to G51 for higher-risk cases).
G45. Sterile strains or strains harvested prior to reproductive maturity should be used (refer to G51 for higher-risk cases).
G46. Seaweed should be planted at an appropriate density to provide it with a competitive advantage over epiphytes and fouling growth.
G47. Cultivation periods should be scheduled to avoid times with high likelihood of pest occurrence.
G48. Stock should be harvested from sea-based farms using appropriate procedures to minimise the risk of stock detachment or release of fouling pests and mesograzers to the environment.
G49. Birds and vermin should be controlled or excluded from production areas.

Additional measures for high and extreme-risk cases
G50. Measures should be put in place to prevent the escape of farmed material, including through vegetative fragments, reproduction or loss of entire thalli.
G51. High-performing cultivars should be farmed in contained systems only.
G52. The external biosecurity risks of local biofouling and ballast water sources should be considered, and appropriate actions should be taken to manage any identified risks (e.g., consider these risks during site selection and contact the port authority to discuss possible risks and raise awareness).
G53. Harvest time should be brought forward if epiphytes or fouling proliferate.

6.4 Equipment, vehicles, and vessels

Objective: Manage the risk of equipment, vehicles or vessels transmitting disease onto, within or from the farm.

Movement of equipment, vehicles and vessels onto the farm

Any equipment, vehicles or vessels that have had direct or indirect contact with aquatic environments, particularly with seaweeds, can transmit pests and diseases onto the farm. The level of risk will depend on the history of use. For example, equipment that has been used at other farms (e.g., harvest bins) or vessels that have been in close contact with stock (e.g., well boats) may present a greater risk. It is important to consider the level of risk and implement appropriate measures to manage risks at entry points to the farm.

Where risks are identified, equipment, vehicles and vessels should be decontaminated prior to being used on the farm. Infrastructure and procedures should be in place to facilitate decontamination. For land-based farms, this may include:

- designated entry points to the farm;
- designated delivery and loading areas;
- cleaning and disinfection facilities;
- equipment storage areas;
- vehicle and vessel parking areas.

For at-sea cultivation, risks may include the introduction of fouling organisms, including seaweed epiphytes and IAS carried on vessels or equipment. Diseases and pest or IAS propagules may also be carried on equipment. New cultivation equipment (e.g., lines, buoys) should be used if possible, or equipment effectively cleaned and decontaminated between crop cycles. Vessels should be decontaminated where appropriate prior to farm visits. For larger vessels and equipment where decontamination is impractical, the appropriate application of anti-fouling and hull maintenance can assist in preventing the spread of disease, pests and IAS by these vectors.

Decontamination procedures should be developed to ensure they are effective for the pathogens of concern (see AQUAVETPLAN – Operational Procedures Manual – Decontamination). Procedures will normally involve initial cleaning followed by disinfection. Disinfection may involve chemical treatment (e.g., chlorine) and/or physical treatment (e.g., drying in direct sunlight). For vessels, biofouling management guidelines are available.

Movement of equipment, vehicles and vessels within the farm

Equipment, vehicles or vessels may transmit diseases between different areas on the farm. This is a particular issue for populations with high health status (e.g., hatcheries), or where production units are to be kept separate.

To manage the risk of spreading disease within the farm, arrangements should be in place to:

- use separate equipment for each production area (the equipment should be labelled and stored appropriately);
- have dedicated facilities in each production area for cleaning and disinfection of routinely used equipment;
- clean and disinfect equipment that must be used in multiple production units;
- Plan vessel movements for at-sea cultivation to limit the risk of spreading pests or disease between different stocks.

Table 22. Guidelines to manage the risk of equipment, vehicles or vessels transmitting pests or pathogens.

Routine measures
G54. Any equipment, vehicles or vessels brought onto the farm should be assessed for biosecurity risk.
G55. Procedures and infrastructure should be in place to clean and disinfect equipment, vehicles and vessels.
G56. The farm should have designated delivery and loading areas, and parking areas for visitors.
G57. Separate equipment should be assigned for use in each area. Where equipment must be used in multiple production units, it should be cleaned and disinfected prior to being moved between units.
G58. Equipment from sea-based farms brought onshore for cleaning and maintenance must be held in designated areas and/or segregated to prevent it from contaminating other equipment involved in at-sea or land-based operations. Equipment must be decontaminated prior to redeployment.
G59. Appropriate anti-fouling should be used for vessels and infrastructure where regular cleaning is impractical.
Additional measures for high and extreme-risk cases
G60. Movements of equipment, vehicles and vessels from areas of known disease status, or from other seaweed aquaculture enterprises, to areas of disease-free status should be avoided. If equipment, vehicles or vessels must be moved, appropriate measures, based on assessed risk, should be implemented. Mitigation strategies may include slipping the boat, removing hull fouling, removing ropes and replacing them with new ropes, disinfecting the vessel, air drying in sunlight, or completing a freshwater rinse.
G61. Equipment that has been in contact with seaweed or seaweed cultivation water external to the farm (including contractor equipment or plant) should not be brought onto the farm. If no alternative exists, a thorough cleaning and disinfection protocol should be followed before entry.
G62. Records of equipment movement should be kept.

6.5 Water

Objective: Manage the risk of water transmitting diseases or pests onto, within and from the farm.

Movement of water onto the farm

A high-quality water source is an important asset to support productivity and seaweed health. The biosecurity risks associated with a water source will depend on the presence of seaweed populations in that water source and their health status, as well as the occurrence of other pest and disease sources.

Other water quality factors need to be considered (e.g., potential for chemical contamination, suspended solids, dissolved gases, salinity and mineral content) because they can impact seaweed health; however, these do not present a direct biosecurity threat and are not considered further in this document.

In some circumstances, water sources may be free of seaweed populations and diseases of concern. Such water sources may include saline groundwater or artificial seawater. These water sources may be particularly suitable for high-health stock if the water quality (salinity etc.) is suitable.

Other water sources, such as oceans, streams or lakes, are likely to contain seaweed populations and may present a risk of disease transmission. In these cases, it may be necessary to provide screening, filtration or disinfection to achieve biosecurity objectives. The treatment required will depend on the likelihood of pest or pathogen entry, and the potential consequences (that is, risk). For valuable, high-health stock, such as genetically improved brood stock, tissue culture explants or gametophyte cultures, a high level of treatment, redundancy and operational maintenance may be required. Water free from contaminants and pathogens is also important for use in spore production, preparation of material for tissue culture, and early nursery cultivation. Where decontamination of water is essential to achieve biosecurity outcomes, there should be regular monitoring to ensure decontamination efficacy is maintained. It may be possible to use the presence of indicator organisms (e.g., ubiquitous non-pathogenic microorganisms) in water as an objective measure of decontamination efficacy.

Numerous options are available to effectively decontaminate water. Decontamination will normally involve filtration to remove particulate matter, followed by disinfection to deactivate any remaining pathogens or pest propagules. Filtration may include multiple steps to progressively remove macroscopic and microscopic particles from the water (e.g., intake screens, sand filters, drum filters, bag filters). The disinfection method should be chosen based on efficacy, cost and environmental impact. Some options include chlorination (followed by de-chlorination), ozonation and ultraviolet irradiation. Autoclaving is ideal for sterilisation but only practical for relatively small volumes, e.g., for use in spore production, micropropagation or preparation of nutrient solutions for small-scale use. Artificial seawater can be used in some cases to ensure sterility, but suitably sterilised natural seawater is typically better for spore production and growth of explants or seedlings. Water should be stored in dark, insulated tanks, and repeated filtration and sterilisation applied prior to use where warranted.

The position of water intakes and outlets for land-based facilities should be considered to minimise contamination from other sources (e.g., other farms) and cross-contamination between the farm's own outlet and intake water.

Movement of water within the farm

The movement of water within a farm should be considered to minimise the potential for pests or diseases to spread between different production units or populations with different health status. This is particularly important to reduce the spread of an emerging disease.

For land-based farms, separate water flows should be used for separate production units or for populations with different health status. This may be achieved by using separate recirculation systems or, for flow-through systems, parallel water flow. Consideration should also be given to sources of spray and aerosols that could spread infection between different populations. Where these are identified, physical barriers may be required.

For sea-based farms, maintaining populations with different health status may be possible through understanding hydrodynamics and carefully considering lease location and arrangement. For example, it may be possible to maintain the different health status of year classes by locating them on leases that are effectively separated (see Section 5.2).

Movement of water from the farm

Appropriate discharge of water will need to be considered where there is a risk of infection or pests spreading to nearby populations of wild or farmed seaweeds, or where there is the risk of spreading IAS or pests and disease of species other than seaweed that could impact other nearby farms or the environment.

Table 23. Guidelines to manage the risk of water transmitting pests or pathogens.

Routine measures
G63. Incoming water should be appropriately treated (e.g., screens on intake pipes, filtration) to minimise the risk of disease or pest entry.
G64. Filtration equipment should be regularly serviced and maintained, and records should be kept. Water treatment should be adequately monitored to ensure it remains effective.
G65. Staff contact with untreated water (e.g., inspecting or maintaining water treatment equipment) should only occur at the end of the day.
G66. Water flow within closed and semi-closed facilities should be designed such that it can prevent disease spread between biosecurity zones.
G67. Water intake and outflow should be positioned to avoid cross-contamination.
G68. Hydrodynamics should be considered in the layout of sea-based farms.
Additional measures for high and extreme-risk cases
G69. Discharge water should be appropriately treated to minimise the risk of disease or pest establishment in the marine environment and transmission to neighboring farms.
G70. Ultraviolet sterilisation, autoclaving or other measures should be applied to ensure adequate water sterility.

6.6 Other farm inputs

Objective: Manage the risk of other farm inputs transmitting disease onto and within the farm.

Other farm inputs may include fertilisers (nutrients, growth promotors) and chemicals. Nutrient solutions that are freshly prepared using inorganic nutrients and sterile water carry little risk, but microscopic contaminants could proliferate in nutrient solutions not appropriately prepared or stored. Fertilisers or growth promotors made from seaweed extracts could also introduce pathogens depending on the method of preparation and the potential for subsequent contamination. Equipment used to prepare, store and deliver fertiliser or other chemicals to seaweed stocks should be cleaned as necessary to prevent contaminants from building up and to reduce the risk of pathogen transmission.

Table 24. Guidelines to manage the risk of other farm inputs transmitting pests or pathogens.

Routine measures
G71. The biosecurity risk posed by other farm inputs should be assessed.
G72. Nutrient media and other additives should be sourced from reputable suppliers.
G73. Solutions should be prepared and stored appropriately.
G74. Fertilisers should be used appropriately; overuse may promote the growth of undesirable epiphytes.
G75. Records on the source and use of nutrients and other inputs should be kept.

6.7 Waste

Objective: Manage the risk of waste transmitting pests or disease onto, within and from the farm.

Waste products may include diseased stock, processing water, processing waste, cleaning effluent, used water filters, fouling, detritus, surplus fertiliser, and surplus or out-of-date treatments. These waste materials may act as a vector for transmitting pests or diseases onto, within and from the farm. It is important that appropriate infrastructure and procedures are in place to ensure waste can be safely disposed. Procedures should detail the methods of disposal for different waste streams and be prepared with consideration of local, state/territory and Australian government requirements.

Equipment used to contain or transport waste materials should be cleaned and disinfected prior to being returned to any production areas.

Table 25. Guidelines to manage the risk of waste materials transmitting pests or pathogens.

Routine measures
G76. Waste products should be assessed to determine the potential biosecurity risks to the farm and the environment.
G77. Waste should be disposed (including via drains) appropriately using regulatory authority-approved methods where relevant.
G78. Waste handling equipment should be decontaminated between uses.
Additional measures for high and extreme-risk cases
G79. High-risk wastewater should be directed down drains away from foot traffic.
G80. High-risk wastewater should be adequately disinfected prior to discharge.
G81. Diseased stock should be contained, and infected stock that is removed should be disposed appropriately. Containment, handling and disposal of diseased stock should minimise identified disease transmission risks through appropriate mitigation measures (e.g., decontamination and disposal protocols and training). The disposal method should pose no risk of pest or pathogen release from the infected stock to waterways, and should allow no access for scavenger birds or animals that could spread a pest or disease.

NB: See also Section 6.3 on management of diseased stock.

7 Emergency procedures

Emergency procedures should be developed and understood to minimise the impact of emergency biosecurity incidents.

Early response actions are critical to reduce the duration and impact of pest and disease outbreaks on your farm. By ensuring clear emergency protocols are developed and understood by all staff, incidents are more likely to be recognised and reported, and appropriate actions taken to limit the spread of pests or diseases. Emergency procedures should include:

- clearly defined triggers for identifying an emergency incident and activating the emergency protocols (e.g., a certain level of unexplained mortality or signs of disease or pest occurrence in a certain proportion of a farm population);
- immediate actions required by staff when an incident is suspected. This may include enhanced biosecurity, reporting the incident to farm management, securing areas to prevent access, and ceasing any activity, such as cleaning, maintenance or movement of water, equipment or stock;
- guidance on observations that should be made to define the circumstances of the incident (e.g., the number of tanks affected, the disease signs observed, the proportion of stock affected);
- procedures for reporting the incident to farm management;
- procedures for contacting relevant persons, such seaweed health experts or the jurisdiction's relevant aquaculture or plant health officer (including any legal reporting obligations);
- guidelines for collecting diagnostic specimens and transporting specimens to the diagnostic laboratory;
- contingency plans for emergency harvest and either use (where appropriate) or destruction and disposal of large volumes of diseased or dead stock;
- protocols for decontaminating ponds, tanks and/or equipment;
- emergency contact details of staff and external authorities.

Table 26. Guidelines on emergency biosecurity procedures.

Routine measures
G82. The farm biosecurity plan should include procedures to respond to an emergency biosecurity incident.
G83. Farm staff should understand the farm's emergency procedures and their own role in an emergency.

8 Legislative and jurisdictional regulatory requirements

Legislation and regulatory requirements for the Australian seaweed industry are likely to be updated as the industry develops, and as specific seaweed biosecurity concerns relevant to Australian jurisdictions and industry are clarified.

Seaweed industry enterprises will need to comply with relevant agency and jurisdictional legislation, and licence conditions.

Table 27. Guidelines for legislative and jurisdictional regulatory requirements.

Routine measures
G84. Import requirements must be adhered to and translocation permits must be obtained for all stock movements where required.
G85. Testing or surveillance must be undertaken in compliance with jurisdictional regulatory requirements.
G86. Commercially farmed species must only be kept on site in accordance with licence conditions.
G87. Chemical or medicine use must comply with relevant state and national legislation (including regulations imposed by the Commonwealth regulator, the Australian Pesticides and Veterinary Medicines Authority).

9 Biosecurity plan monitoring and audit

The biosecurity plan should be reviewed routinely to ensure it continues to address biosecurity risks effectively and efficiently, and that only the minimum level of resources is required for effective implementation.

Triggers for an extraordinary review of the plan may include changes in farm operations, such as increased production, construction of new production units, changes to husbandry approaches or the occurrence of a biosecurity incident.

Routine auditing can be used to ensure the plan is being implemented appropriately and to identify any operational deficiencies. Internal audits should be routinely carried out and documented. An independent third-party audit will provide stronger assurance to customers or regulators that plans and procedures are being followed, and that quality management systems are effective. A third-party (external) audit may be required for formal acceptance of the plan in some cases, e.g., if you need to obtain approval for translocation.

Table 28. Guidelines for biosecurity plan monitoring and audit.

Routine measures
G88. The farm biosecurity plan should include a schedule for routine review, and triggers that would prompt an extraordinary review should be identified.
G89. An audit of the farm biosecurity plan (and effective record keeping of formal audits) should be conducted to ensure it is being implemented effectively.

10 Record keeping and documentation

Record keeping of necessary information supports good biosecurity practice in accordance with the farm biosecurity plan.

10.1 Stock movements

Records of stock movements and inventory (see G25 and G26) are essential for tracing activities in the event of a disease or pest outbreak. At a minimum, it is recommended to record:

- The source of stock introduced to the farm, including the original and most recent source (if different);
- movement of stock within the farm (particularly if between different biosecurity zones);
- movement of stock between farm operations, e.g., from the nursery to grow-out.

Records for each movement should, at a minimum, include:

- the date of movement;
- the batch identifier;
- the quantity of stock;
- the buyer, including contact details for stock sold to other enterprises (e.g., sale of hatchery stock for grow-out);
- the origin of stock, including contact details for purchased stock/

10.2 Stock health and water quality

Health and performance records (see G28) provide evidence that you are regularly monitoring stock. Information on the health status of stock and water quality will assist in identifying any emerging disease issues and optimising husbandry conditions. Records of other farm inputs (see G75) should form part of the husbandry records. Farm input records will also assist in identifying potential sources for any outbreak.

Stock health and water quality records should include:

- observations on health status, including details of any disease or pest signs or mortality;
- husbandry records (e.g., stocking densities, growth rates, nutrients and other additives);
- application of treatments;
- details of failed batches;
- disposal method used where applicable;
- water quality and/or environmental data;
- results of disease or other health testing.

10.3 People and equipment

Records of staff and visitors (see G17) and equipment movement and use (see G62) can assist with tracing the possible origin of a pest or disease outbreak, and determining the possible extent of spread within or beyond the farm. The amount of detail required will depend on the circumstances of the farm and the assessed risk.

Where the assessed risk is high or extreme, it is recommended to record:

- specific locations (other farms, areas with wild seaweed) visited by staff/visitors or where equipment was used prior to entering the farm;
- areas visited within the farm;
- details of mitigation measures (e.g., decontamination) applied prior to entry or to movement between zones.

10.4 Other records

Other records that should be kept include details of biosecurity plan audits, document control information, and revisions to the farm biosecurity plan. Note key outcomes and audit recommendations for reference and to demonstrate that you are critically reviewing your plan. Include brief but specific notes of any findings or required corrections, or refer to a detailed document containing this information.

Keeping these records ensures you have evidence that demonstrates your plan is being maintained as a living document and is continually reviewed and updated based on:

- changed biosecurity threats;
- ongoing learnings;
- infrastructure upgrades;
- changes in farm practices;
- newly available risk management tools or information;
- audit recommendations.

While it is important to capture key information, records management should be as simple and practical as possible, and not include extraneous detail. Templates to cover a range of record keeping requirements are available on the Farm Biosecurity website, and include:

- training records;
- visitor register;
- stock receipt and inspection records;
- visitor/staff risk assessment;
- cleaning records;
- audit records.

10.5 Supporting documents

Maintain associated documents that are referenced within your farm biosecurity plan. These include SOPs, checklists, staff training records and record-keeping templates (see Section 12). Checklists are essential supporting documents that should be used in conjunction with SOPs wherever possible. They provide the evidence that an accountable staff member is following procedures outlined in an SOP at correct intervals. Having a list of associated documents ensures you can readily identify supporting documents and can make them accessible for review and audit. You do not need to include the supporting documents in the body of your plan; keep them elsewhere (to ensure version control is preserved) or include them as appendices.

Table 29. Guidelines for record keeping and documentation.

Routine measures
G90. Detailed records of stock movements and inventory should be maintained and be readily accessible (see G25 and G26).
G91. Detailed records of stock health, mortality, husbandry and water quality should be maintained and be readily accessible (see G28 and G75).
G92. Visitor, staff and equipment logs should be maintained (see G17 and G62; refer to G97 for higher-risk cases).
G93. Records of staff training should be kept.
G94. Dates and outcomes of internal and external audits should be recorded.
G95. Document control and a revision record should be included in your biosecurity plan.
G96. A list of supporting documents should be included in your biosecurity plan, and these documents should be readily accessible.
Additional measures for high and extreme-risk cases
G97. Detailed records on staff, visitor and equipment movements, and on mitigation measures applied before entry to, exit from or movement between areas, should be kept.

Part 3 Biosecurity risk analysis

11 Risk analysis process

Risk analysis is an accepted approach for evaluating biosecurity risks. Risk analysis can be used to focus a biosecurity plan on the highest risks to farm productivity and to ensure investments in biosecurity, through the biosecurity plan, deliver maximum benefit.

11.1 Risk analysis steps

Step 1 of risk analysis is hazard identification – identifying the pests and diseases that could produce adverse consequences to seaweed health and your farm's productivity. Hazard identification will determine which pests and/or pathogens should be subject to a risk assessment (Stage 2). See Section 3 for a summary of potential hazards to seaweeds. New diseases emerge regularly in aquaculture, and with cultivation of novel seaweed species and the establishment of seaweed farms in new areas, the likelihood of new diseases emerging is particularly high for seaweed farms. Hazard identification for seaweed farms should therefore consider emerging pest and diseases hazards.

Step 2 of risk analysis is risk assessment – completed by estimating the relative levels of likelihood and consequence of a pest or disease entering (or proliferating within) your farm. The assessments can vary widely in complexity; from using detailed research and statistical approaches (quantitative), to basic estimates based on previous experience and circumstances (qualitative).

Risk is determined as a product of likelihood and consequence. This means that a disease that presents major consequences (e.g., would result in complete depopulation of the farm) could be a low risk if the likelihood of it occurring is remote (e.g., because it is an exotic disease and there are no realistic pathways of entry onto your farm). A risk matrix is a simple, standard approach for determining risk from estimates of likelihood and consequence.

Step 3 of risk analysis is risk management – implementing measures to reduce the identified risks to an acceptable level. The preferred option should be practical, effective and value for money.

11.2 Risk assessment

To assign a level of risk to a hazard, two factors need to be determined – the likelihood of occurrence on your farm and the consequences to your farm from it occurring. For the risk assessment, you should consider the likelihood and consequence in the absence of any mitigation measures being applied (unmodified or uncontrolled risk).

Likelihood

Likelihood can be estimated by considering the pathways necessary for entry, spread or release of an IAS, pest or disease, and for exposure of your stock to the pest or pathogen. For example, the likelihood of entry and exposure might be 'certain' for a pathogen that occurs in untreated intake water or for opportunistic pathogens that are routinely found on healthy seaweeds. The likelihood rating will vary depending on the properties of the pest or disease, the occurrence of the pest or disease outside the farm, and possible pathways onto the farm. Likelihood ratings and descriptors are shown in Table 30.

Table 30. Assessment of likelihood.

Rating	Descriptor
Remote (1)	Never heard of but not impossible here; occurs less than once in 20 years.
Unlikely (2)	May occur here but only in exceptional circumstances; occurs more than once in 20 years.
Possible (3)	Clear evidence to suggest this is possible here; occurs more than once in three years
Likely (4)	It is likely, but not certain, to occur here; occurs more than once in two years (>50%).
Certain (5)	It is certain to occur; occurs every year.

Consequence

Consequence can be estimated by considering the impacts of a pest or disease on the productivity of your farm. There can be multiple consequences (e.g., mortality, reduced growth or product quality, market access, treatment costs). Consequences for environmental hazards (e.g., the introduction or spread of IAS by farm activities) are typically considered in broader risk assessments used to determine cultivation areas or by authorities when deciding whether to issue a licence. You should, however, consider the consequences of any relevant hazard to your farm operation, e.g., the consequences of breaching general biosecurity obligations where applicable. Consequence ratings and descriptors are shown in Table 31.

Table 31. Assessment of consequences.

Rating	Descriptor
Insignificant (1)	Impact not detectable or minimal.
Minor (2)	Impact on farm productivity limited to some production units or the short term only.
Moderate (3)	Widespread impact on farm productivity due to increased mortality or reduced performance.
Major (4)	Considerable impact on farm productivity resulting in serious supply constraints and financial impact.
Catastrophic (5)	Complete depopulation of the farm and possibly barriers to production resuming.

Risk estimation

Risk is estimated as a product of likelihood and consequence, resulting in risk ratings of 1 to 25. Risks are highest when ratings for both likelihood and consequences are high. However, risks may be low if the consequence is ‘catastrophic’ but the likelihood is ‘remote’; or if the likelihood is ‘certain’ but the consequence is ‘insignificant’. Risk ratings can be determined by applying estimates of likelihood (where 1 is remote and 5 is certain) and consequence (where 1 is insignificant and 5 is catastrophic) to a risk matrix (Figure 18).

Consequence rating

Likelihood rating	Insignificant	Minor	Moderate	Major	Catastrophic
Remote	1	2	3	4	5
Unlikely	2	4	6	8	10
Possible	3	6	9	12	15
Likely	4	8	12	16	20
Certain	5	10	15	20	25

Risk level	Explanation and management response
1–2 Negligible	Acceptable level of risk. No action required.
3–5 Low	Acceptable level of risk. Ongoing monitoring may be required.
6–10 Medium	Unacceptable level of risk. Active management is required to reduce the level of risk.
11–15 High	Unacceptable level of risk. Intervention is required to mitigate the level of risk.
16–25 Extreme	Unacceptable level of risk. Urgent intervention is required to mitigate the level of risk.

Figure 18. Risk estimation matrix.

11.3 Identifying risk management measures

Risk management involves identifying measures to reduce the identified risks to an acceptable level.

Evaluating risks: Medium, high and extreme risks should be considered unacceptable. Management measures to reduce these risks to acceptable levels would form part of the farm biosecurity plan. Low risks may not require specific mitigation measures but may warrant some level of ongoing monitoring to identify whether the risk profile changes over time.

Risk management options: Numerous risk management options may be available to reduce risks to an acceptable level. The preferred option should be chosen based on its practicality, effectiveness and cost. Risk management options may reduce likelihood, consequence or both. For example, having access to an effective disease treatment would have no influence on the likelihood of entry of that pathogen, but may reduce the consequences significantly.

The effectiveness of risk management measures can be assessed by performing a risk assessment considering the likelihood and consequence of a pest or disease with the relevant measures in place (modified risk), thus ensuring that this modified risk is acceptably low.

11.4 Documenting the risk analysis process

The risk analysis process should be documented so that risks and risk management measures can be easily reviewed as a part of routine biosecurity plan monitoring and audit. This will also ensure you record the rationale for specific measures in the biosecurity plan. Table 32 provides an example of how risk analysis can be recorded concisely.

Table 32. Example of risk analysis recording.

Hazard	Likelihood	Consequence	Unmodified risk rating	Management response and control measures	Modified risk rating
Entry and spread of 'disease X' onto and within the farm	Possible. The disease is endemic and occurs in wild seaweed stocks. Farm outbreaks have been recorded previously.	Moderate. Likely to result in considerable stock losses.	9 (medium)	Mitigation measures are required to reduce risk. Likelihood reduced by sourcing stock only from hatcheries with audited biosecurity plans, including measures to prevent the disease. Consequences reduced by keeping new stock in separate production units with the ability to effectively isolate should a disease occur.	Control measures reduce the likelihood to 'unlikely' and the consequence to 'minor'. Measures reduce the risk rating to 4 (low). The modified risk is acceptable.

Part 4 Biosecurity plan implementation

Following development of your biosecurity plan, it will need to be implemented with the cooperation of farm management and staff. Implementation may require changes to how your farm operates, such as new or altered procedures, new equipment, new or altered farm infrastructure, new signs and new or altered record-keeping methods.

It is important that staff are fully aware of any new responsibilities under the farm biosecurity plan and clearly understand their role. Staff consultation in developing new procedures may improve practicality and efficiency. Ensuring staff are familiar with new procedures and are trained as needed (Section 6.2) is also important.

If the implementation of the biosecurity plan requires extensive changes, these may need to be phased in over a reasonable time period. This would allow time for staff consultation and training on the most suitable approaches, and for any new equipment to be deployed or existing equipment or facilities to be modified.

If implementation must be phased in over time, it would be logical to focus first on biosecurity measures that mitigate the highest biosecurity risks.

12 Standard operating procedures

New biosecurity processes may need to be described in a standard operating procedure (SOP) if they are complex, rarely performed, performed by multiple staff, or critical to maintaining farm biosecurity. If a quality management system has been implemented on your farm, biosecurity SOPs should be incorporated within that quality system.

A SOP aims to support consistent performance of a particular function by farm staff. For this reason, it must be clear, easy to follow and available to staff in areas where the function is performed. Table 33 is a template for a biosecurity SOP.

Depending on the size and scale of your farm, and the number of staff employed, you may wish to incorporate multiple topics into the same SOP, or have a separate SOP for each procedure. The following SOPs are suggested as a minimum:

- New employee induction and training procedure
- Farm visitor procedure
- Stock arrivals, movement and dispatch procedure(s)
- Health inspection procedure(s)
- Procedure for the collection and disposal of mortalities, diseased stock and other wastes
- Disinfection procedure(s)
- Farm biosecurity zones
- Emergency response plan.

Table 33. Template for a biosecurity standard operating procedure.

SOP section	Explanation
Title	This should be clear and unambiguous (e.g., emergency procedures for high mortality).
Objective	This should be clear and unambiguous (e.g., describe procedures to be followed in the event of high, unexplained mortality or specific disease signs on the farm).
Responsibilities	Describe who the SOP applies to and the roles they must perform. For example: All staff: Understand this procedure, be able to follow initial response actions, report to biosecurity manager. Biosecurity manager: Coordinate initial response, report to farm manager, liaise with relevant seaweed health expert(s) and/or diagnostic laboratories. Farm manager: Responsible for deciding on response actions and reporting to government authorities where required.
Procedure	Clearly describe the steps that should be taken as appropriate. For example: 1. Cease all activity, including cleaning and stock movement. 2. Check water quality and other relevant parameters. such as flow, temperature, light. 3. Isolate water flows to/from the affected stock/production areas. 4. Secure the area to prevent access by unnecessary personnel, and to prevent movement of equipment or stock. 5. Assess the extent of the situation. How many tanks/ponds/cultivation lines are affected? What is the proportion of stock affected? What disease signs are apparent?
Precautions	Clearly describe any activities that must be avoided. For example: 1. Staff must not visit other production areas of the farm. 2. Equipment and stock must not leave the affected area.
Review date and further information	The SOP should include the date it came into effect and any supporting information, and should cross-reference the relevant component of the farm biosecurity plan.

13 Signage

Your biosecurity plan may require that new signs be erected at access points, to label different production areas and to identify restricted areas. Signs can be purchased from several providers. Links to buy signs and templates to make signs are provided on the Farm Biosecurity website.

Part 5 Generic biosecurity plan template

Guidelines		Management response	Responsibility	By when	Resources
G1.	Land-based farms should have a secure perimeter fence or otherwise well-defined boundary, establishing a clearly defined biosecurity zone. Entrances to the property should be able to restrict vehicle and foot traffic, and should be locked during non-visitor hours.				
G2.	Production units (e.g., sheds, ponds, tanks, raceways, longlines) should have a unique and permanent identifier.				
G3.	Farm maps and diagrams showing relevant biosecurity zones should be available (see Section 5).				
G4.	Relevant information for key internal and external contacts should be readily available (see Section 5).				
G5.	Staff and visitor access should be managed (through access controls and signage), and the risk they present should be assessed.				
G6.	The farm biosecurity rules should be explained to all visitors.				
G7.	Measures to prevent disease entry should be applied to all persons entering and exiting the farm (e.g., dedicated changing areas, farm footwear and handwashing facilities), and, if assessed as necessary, to persons moving between different production areas within the farm. For high or extreme-risk cases, see G15 and G16.				
G8.	Production units should be managed separately to reduce the risk of disease spread within the farm. Staff should be assigned to production units based on risk.				
G9.	Staff should wear freshly laundered clothes daily and change into designated farm-only footwear on entry.				

Guidelines		Management response	Responsibility	By when	Resources
G10.	Staff should record overseas travel and declare contact with other aquaculture facilities.				
G11.	Staff should receive annual training in pest and disease identification, and the steps involved in recording, reporting and investigating disease events.				
G12.	Divers should disinfect all equipment between visiting different leases or areas with stock from different cultivation cycles.				
G13.	Access to sensitive areas (e.g., hatcheries, quarantine areas) should be restricted to dedicated, authorised staff only.				
G14.	If staff must work in multiple production units or zones, movements should be ordered from zones with the highest health status stock (i.e., with lesser likelihood of having a pest or disease) to the lowest health status stock (i.e., with greater or unknown likelihood of having a pest or disease), while considering the specific hazards and risk profile of each zone and activity. Appropriate decontamination procedures should be applied if movements assessed as high risk are unavoidable.				
G15.	Visitors should complete a biosecurity declaration on arrival to ensure their risk to hatchery biosecurity can be assessed. Consider refusing entry to high-risk visitors.				
G16.	Visits should be unidirectional (as per G14). Visitors should be accompanied by a staff member at all times.				
G17.	Records of staff and visitor movements should be kept.				
G18.	Staff should be prohibited from visiting other seaweed aquaculture sites or undertaking activities (including recreationally) that carry a risk of contact with relevant wild seaweeds before entering the farm (unless they have followed your SOPs to mitigate disease risks, including appropriate decontamination where required).				

Guidelines		Management response	Responsibility	By when	Resources
G19.	Staff and visitors should be prohibited from bringing uncooked seafood products or bait to the workplace.				
G20.	A staff member should be made responsible for overseeing farm biosecurity.				
G21.	Staff should understand the disease risks to the farm, the role of the farm biosecurity plan in managing disease risks, and their responsibilities for its implementation, including response protocols.				
G22.	Staff should receive training on the aspects of the farm biosecurity plan relevant to their work, and have access to the farm biosecurity plan and supporting procedures.				
G23.	The health of all stock introduced to the farm should be assessed, and records of the source and the date of introduction of all stock kept. Translocation approvals or permits must be obtained if required by the receiving state or territory authority. See G34 for cases of higher risk.				
G24.	Movement of stock between different farm populations should only occur after the disease risks have been considered, and with a view to maintaining high health status stock.				
G25.	Movement records should be maintained for all stock moved onto the farm, between zones of different biosecurity status within the farm, and from the farm.				
G26.	Stock management activities, including harvest, cleaning and adding treatments, should be recorded.				
G27.	Stock used for out-planting to semi-open (e.g., at-sea cultivation) or open (e.g., to replenish or restore wild stocks) systems should be of high health status.				

Guidelines		Management response	Responsibility	By when	Resources
G28.	Stock health should be inspected regularly and observations should be recorded. Health monitoring records should be kept for different stock populations within the farm, and should include details of any disease signs, mortality, treatments, disease testing and relevant environmental information.				
G29.	Health problems should be investigated with the assistance of relevant experts where needed. The farm should have the capability to rapidly collect and preserve samples for investigations.				
G30.	Stock showing signs of disease or pest infection should be isolated until the cause is known and the situation is resolved.				
G31.	Stock stress should be minimised by ensuring appropriate water quality, lighting, stocking density, fertilisation and handling.				
G32.	Different stock (e.g., stock from different cultivation cycles) should be maintained in separate areas (land-based) or leases (sea-based).				
G33.	Fallowing periods or crop rotation should be implemented.				
G34.	Stock being introduced to the farm should have a known health status that is equal or better than stock already on the farm.				
G35.	If the health status of stock being introduced to the farm is unknown (e.g., wild brood stock or seed stock of unknown health status), the material should be isolated from other farm populations in separate production units or dedicated quarantine facilities.				
G36.	Quarantine of high-risk brood stock should be lifelong with a view to producing high-health or specific-pathogen-free progeny that would become brood stock.				
G37.	Where feasible, quarantined stock should be treated to mitigate disease risks. Treatments must be conducted in accordance with legislative and regulatory requirements.				

Guidelines		Management response	Responsibility	By when	Resources
G38.	Diseased stock that is not able to be isolated, and any material showing signs of severe disease (e.g., necrotic tissue), should be removed from production units/leases as soon as possible.				
G39.	Stock removed from cultivation should be managed to minimise risk to other farmed and wild stocks. Where removed stock must be disposed, appropriate disposal methods should be used; do not return removed stock to the environment.				
G40.	The farm should have equipment and contingency plans to manage diseases and to accommodate emergency harvest or disposal of large stock volumes (e.g., capacity to store and process high volumes of harvested stock or pre-arranged high-volume disposal sites and methods). Alternative uses for stock, e.g., in composts, may be considered where the risks of use are acceptable.				
G41.	In semi-closed systems, intakes should be positioned away from wild seaweed stocks and entry of aquatic animals (especially mesograzers), and pest propagules in the water supply should be prevented (see also Section 6.4).				
G42.	In semi-open systems, locations should be considered with respect to wild seaweeds and options to limit access by herbivorous fish to production units.				
G43.	For at-sea cultivation, systems should be used that are suitably robust for the conditions, and infrastructure should be regularly inspected.				
G44.	Genetically diverse local cultivars or appropriate disease-resistant strains should be used (refer to G51 for higher-risk cases).				
G45.	Sterile strains or strains harvested prior to reproductive maturity should be used (refer to G51 for higher-risk cases).				
G46.	Seaweed should be planted at an appropriate density to provide it with a competitive advantage over epiphytes and fouling growth.				
G47.	Cultivation periods should be scheduled to avoid times with high likelihood of pest occurrence.				

Guidelines		Management response	Responsibility	By when	Resources
G48.	Stock should be harvested from sea-based farms using appropriate procedures to minimise the risk of stock detachment or release of fouling pests and mesograzers to the environment.				
G49.	Birds and vermin should be controlled or excluded from production areas.				
G50.	Measures should be put in place to prevent the escape of farmed material, including through vegetative fragments, reproduction or loss of entire thalli.				
G51.	High-performing cultivars should be farmed in contained systems only.				
G52.	The external biosecurity risks of local biofouling and ballast water sources should be considered, and appropriate actions should be taken to manage any identified risks (e.g., consider these risks during site selection and contact the port authority to discuss possible risks and raise awareness).				
G53.	Harvest time should be brought forward if epiphytes or fouling proliferate.				
G54.	Any equipment, vehicles or vessels brought onto the farm should be assessed for biosecurity risk.				
G55.	Procedures and infrastructure should be in place to clean and disinfect equipment, vehicles and vessels.				
G56.	The farm should have designated delivery and loading areas, and parking areas for visitors.				
G57.	Separate equipment should be assigned for use in each area. Where equipment must be used in multiple production units, it should be cleaned and disinfected prior to being moved between units.				

Guidelines		Management response	Responsibility	By when	Resources
G58.	Equipment from sea-based farms brought onshore for cleaning and maintenance must be held in designated areas and/or segregated to prevent it from contaminating other equipment involved in at-sea or land-based operations. Equipment must be decontaminated prior to redeployment.				
G59.	Appropriate anti-fouling should be used for vessels and infrastructure where regular cleaning is impractical.				
G60.	Movements of equipment, vehicles and vessels from areas of known disease status, or from other seaweed aquaculture enterprises, to areas of disease-free status should be avoided. If equipment, vehicles or vessels must be moved, appropriate measures, based on assessed risk, should be implemented. Mitigation strategies may include slipping the boat, removing hull fouling, removing ropes and replacing them with new ropes, disinfecting the vessel, air drying in sunlight, or completing a freshwater rinse.				
G61.	Equipment that has been in contact with seaweed or seaweed cultivation water external to the farm (including contractor equipment or plant) should not be brought onto the farm. If no alternative exists, a thorough cleaning and disinfection protocol should be followed before entry.				
G62.	Records of equipment movement should be kept.				
G63.	Incoming water should be appropriately treated (e.g., screens on intake pipes, filtration) to minimise the risk of disease or pest entry.				
G64.	Filtration equipment should be regularly serviced and maintained, and records should be kept. Water treatment should be adequately monitored to ensure it remains effective.				
G65.	Staff contact with untreated water (e.g., inspecting or maintaining water treatment equipment) should only occur at the end of the day.				
G66.	Water flow within closed and semi-closed facilities should be designed such that it can prevent disease spread between biosecurity zones.				

Guidelines		Management response	Responsibility	By when	Resources
G67.	Water intake and outflow should be positioned to avoid cross-contamination.				
G68.	Hydrodynamics should be considered in the layout of sea-based farms.				
G69.	Discharge water should be appropriately treated to minimise the risk of disease or pest establishment in the marine environment and transmission to neighboring farms.				
G70.	Ultraviolet sterilisation, autoclaving or other measures should be applied to ensure adequate water sterility.				
G71.	The biosecurity risk posed by other farm inputs should be assessed.				
G72.	Nutrient media and other additives should be sourced from reputable suppliers.				
G73.	Solutions should be prepared and stored appropriately.				
G74.	Fertilisers should be used appropriately; overuse may promote the growth of undesirable epiphytes.				
G75.	Records on the source and use of nutrients and other inputs should be kept.				
G76.	Waste products should be assessed to determine potential biosecurity risk to the farm and the environment.				
G77.	Waste should be disposed (including via drains) appropriately using regulatory authority-approved methods where relevant.				
G78.	Waste handling equipment should be decontaminated between uses.				
G79.	High-risk wastewater should be directed down drains away from foot traffic.				

Guidelines		Management response	Responsibility	By when	Resources
G80.	High-risk wastewater should be adequately disinfected prior to discharge.				
G81.	Diseased stock should be contained, and infected stock that is removed should be disposed appropriately. Containment, handling and disposal of diseased stock should minimise identified disease transmission risks through appropriate mitigation measures (e.g., decontamination and disposal protocols and training). The disposal method should pose no risk of pest or pathogen release from the infected stock to waterways, and should allow no access for scavenger birds or animals that could spread a pest or disease.				
G82.	The farm biosecurity plan should include procedures to respond to an emergency biosecurity incident.				
G83.	Farm staff should understand the farm's emergency procedures and their own role in an emergency.				
G84.	Import requirements must be adhered to and translocation permits must be obtained for all stock movements where required.				
G85.	Testing or surveillance must be undertaken in compliance with jurisdictional regulatory requirements.				
G86.	Commercially farmed species must only be kept on site in accordance with licence conditions.				
G87.	Chemical or medicine use must comply with relevant state and national legislation (including regulations imposed by the Commonwealth regulator, the Australian Pesticides and Veterinary Medicines Authority).				
G88.	The farm biosecurity plan should include a schedule for routine review, and triggers that would prompt an extraordinary review should be identified.				
G89.	An audit of the farm biosecurity plan (and effective record keeping of formal audits) should be conducted to ensure it is being implemented effectively.				

Guidelines		Management response	Responsibility	By when	Resources
G90.	Detailed records of stock movements and inventory should be maintained and be readily accessible (see G25 and G26).				
G91.	Detailed records of stock health, mortality, husbandry and water quality should be maintained and be readily accessible (see G28 and G75).				
G92.	Visitor, staff and equipment logs should be maintained (see G17 and G62; refer to G97 for higher-risk cases).				
G93.	Records of staff training should be kept.				
G94.	Dates and outcomes of internal and external audits should be recorded.				
G95.	Document control and a revision record should be included in your biosecurity plan.				
G96.	A list of supporting documents should be included in your biosecurity plan, and these documents should be readily accessible.				
G97.	Detailed records on staff, visitor and equipment movements, and on mitigation measures applied before entry to, exit from or movement between areas, should be kept.				

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