Scoping the need and feasibility for offshore Pacific oyster aquaculture in Tasmania

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Final Project Report

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The CRC Program supports industry-led collaborations between industry, researchers and the community.

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Executive Summary

Tasmanian oyster farmers contribute approximately one third of the total Australian oyster production of 9,000 tonnes. While globally, oyster aquaculture produced 6 million tonnes in 2020. The substantial domestic appetite for oysters is evident through the considerable quantities of imported oysters consumed in Australia, with over 8,000 tonnes of frozen oysters sourced from New Zealand annually. Considering the global oyster production levels and the consistent demand in the oyster market, the Tasmanian industry is presented with a significant opportunity for expansion.

The aims for this scoping project were:

- Define the need for offshore or higher energy water expansion within the Tasmanian Pacific oyster industry;
- Provide a brief review of global approaches to offshore oyster aquaculture; and
- Assess the feasibility of offshore aquaculture in Tasmania – identifying key considerations and challenges, knowledge gaps, and opportunities.

This scoping project involved reviewing examples of global research in offshore oyster farming and describing initiatives from several countries that have invested significantly in offshore oyster research. Overseas, spatial limitations and increasing demand for high quality domestically produced seafood have led oyster producers to explore offshore farming. International research projects have provided very promising results for offshore oyster farming, and this gives further assurance that oyster farming expansion to higher energy environments is likely to be viable in Tasmania if approached in the right way.

We also brought the Tasmanian industry into the discussion, holding theme meetings that interested farmers were encouraged to join. In these meetings the experts and industry stakeholders were briefed on the literature review findings and encouraged to provide feedback and commentary. Production expansion opportunities were identified in the number of unlicensed oyster leases located in deeper, higher energy waters around Tasmania.

However, several farmers raised concerns of barriers to developing the vacant leases, including equipment suitability, logistical concerns, and a lack of confidence around the primary productivity of higher energy sites to justify investment. The project identified that research, development, and extension through the Blue Economy CRC could address these barriers and afford the Tasmanian oyster industry a way forward to offshore farming.

Key themes emerged from the literature review, including, assessing site suitability, the importance of efficient farm systems and processes, offshore growth performance, challenging physical conditions and biofouling.

Key knowledge gaps identified include:

- Limited data on local environmental conditions hindering a developed understanding of offshore site potential.
- Uncertainty about the applicability of inshore site selection models to offshore settings.
- Limited information of the specific traits that should be targeted in selective breeding for offshore oyster farming.

- An absence of return-on-investment data and clear comparisons of quality attributes between offshore and inshore oysters, impacting the economic viability and pricing of offshore oyster production.
- An absence of specialised, durable equipment, more efficient and automated processes.

This scoping project concluded by outlining a recommended three-part approach for the Tasmanian oyster industry within the remaining years of the Blue Economy CRC.

Table 1: Research approach for the Tasmanian oyster industry in the Blue Economy CRC.

Component	Broad research category
Part 1	Scoping Project
Part 2	Understanding site suitability and potential Oyster performance and economics: criteria, techniques, and approaches
Part 3	Equipment, engineering, and field assessment

1. Introduction

In recent times traditional coastal aquaculture has faced numerous limitations and challenges. Many aquaculture sectors are considering offshore farming to counter adverse impacts associated with more nearshore and land-based farms and to afford expansion (Froelich et al., 2017). Competition for space in the nearshore coastal zone is one of the leading causes for stagnation within the aquaculture sector (Palmer et al., 2021). Oyster farms have historically utilised intertidal zones, and oyster production is intrinsically limited by this spatial confinement (Barillé et al., 2020). Offshore aquaculture has the potential to address the spatial limitations and environmental challenges faced by farmers in the intertidal zone.

The term "Offshore Aquaculture" can encompass various types of farming systems based beyond the coast, but there is no one clear definition (Fujita et al., 2023). The conventional understanding implies that marine organisms are cultured in the open ocean, far from the coastline. However, in practice, it does not necessarily require traveling significant distances from the shore or operating at deeper depths (Soto & Wurmann, 2019). There is an interplay of metrics such as depth, distance from shore, and current, which can vary vastly between different examples of offshore culture systems (Froehlich et al., 2017). For this review, the term offshore will be defined as being the antithesis of ‘’onshore’’ or occurring outside of ‘’nearshore waters’’ (greater than 3 nm from the coast) and may also include reference to high energy environments nearshore environments.

Offshore offers a solution to competition for space as well as satisfying public interest, which encompasses the collective welfare, environmental concerns, and societal benefits associated with marine resource utilisation. Offshore aquaculture facilities are typically larger than their nearshore counterparts (Krause & Mikkelsen, 2017). Increased size can also enable farmers to take advantage of economies of scale and achieve higher production volumes, or if a burgeoning farmer, a production rate in line with the capital they are able to invest (Barillé et al. 2020). The size of an offshore aquaculture facility will depend on a variety of factors, including the local environmental conditions, and the availability of infrastructure and support services. In some cases, smaller-scale operations may be more appropriate or feasible, particularly in areas with limited access to capital or technical expertise.

Over the past decade, numerous countries have funded research and development of oyster cultivation in offshore environments totalling $22.6 million US globally since 2015. In Europe, where coastal areas face spatial limitations and pollution effects, oyster producers from countries such as France, Germany, and Belgium are shifting focus to exploring farming beyond traditional intertidal areas, aiming to enable the growth of their industry (Barillé et al., 2020, Galparsoro et al., 2020, Pogoda et al., 2011). This shift is partially motivated by the increasing demand for domestically produced seafood and, in the case of Belgian producers, the desire to enhance the value of their product by expanding high-value European flat oyster production (Holm et al., 2017, Colruyt Group, 2022). In New Zealand, competition for inshore space is recognised as a hurdle for new aquaculture ventures. However, the primary impetus behind investing in offshore aquaculture lies in its strong economic potential (Heasman et al.,2020).

Like the challenges aquaculture faces globally, the oyster industry in Tasmania has similar constraints impeding its ability to expand production. Recognising this challenge, the Blue Economy CRC identified Pacific oyster farming as potential candidate for their research portfolio, and Oysters Tasmania was approached as a possible research partner. The Oysters Tasmania Board directed their RD&E Sub-Committee to make a recommendation on how to proceed with this proposal. The OT RD&E SC recommended a three-part approach: Part 1 – Scoping; Part 2 – gather information required to guide Part 3; and Part 3 – field-based Research and Development.

The primary aim of this study is to define a stop-go to the next stage; and if a go decision determined – provide a framework for Part 2, including work to understand how local environmental factors impact physical site suitability and productivity, determination of experimental design factors for field trials of oysters in BE-CRC, and explore the potential role of genetic selection in enhancing offshore oyster traits.

The objectives of the initial scoping stage:

1. Define the need for offshore or higher energy water expansion within the Tasmanian Pacific oyster industry;
2. Provide a brief review global approaches to offshore oyster aquaculture; and
3. Assess the feasibility of offshore aquaculture in Tasmania – identifying key considerations and challenges, knowledge gaps and opportunities.

1.1. Pacific Oyster Farming in Tasmania

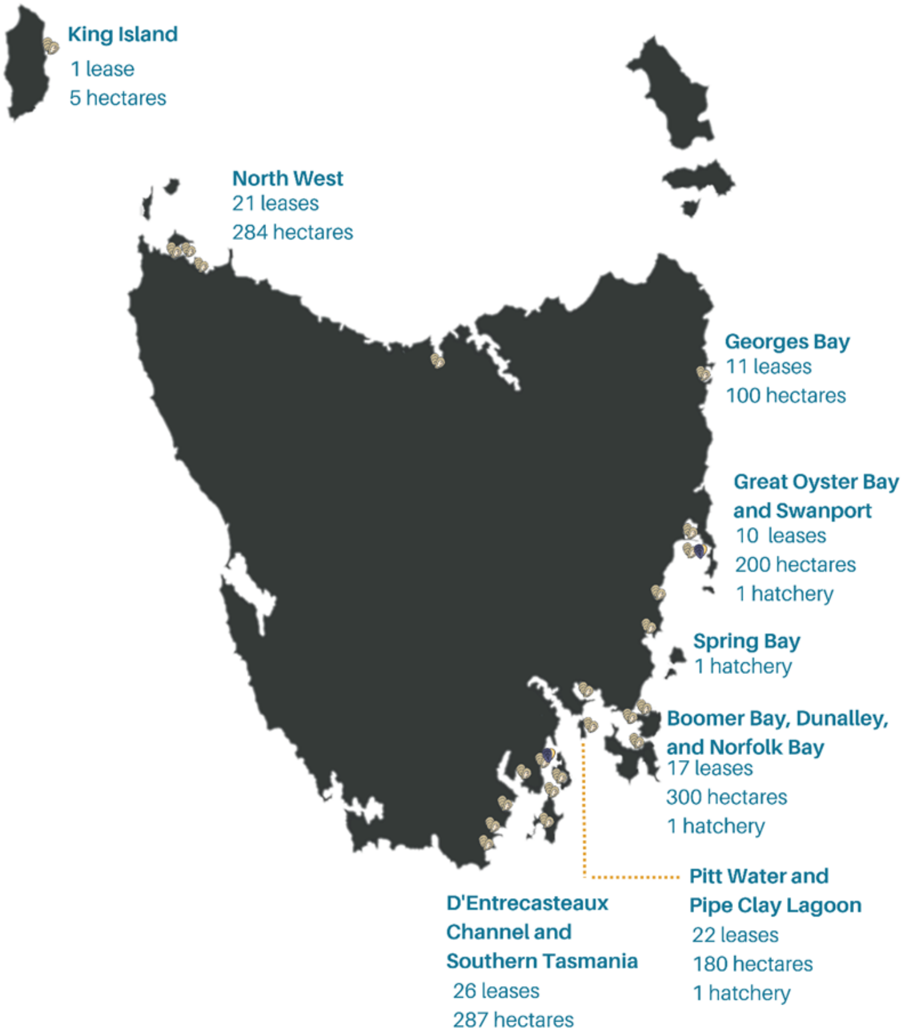


Figure 1. Geographical distribution and lease allocation and size of Tasmanian oyster growing regions.

Most Tasmanian oyster farms are within sheltered estuaries located in the north-west, east coast, and south-east regions of the state (Figure 1). As of July 2022, a total of 1246 licensed hectares of marine leases were dedicated to oyster production, distributed across 99 marine leases operated by 42 farming companies

(Department of Natural Resources and Environment Tasmania, 2022). Four land-based hatcheries deliver single seed oyster spat for the entire industry (Department of Natural Resources and Environment Tasmania, 2022). Spat are subsequently moved to semi-closed nursery systems, then grown out on intertidal and subtidal marine leases until they attain harvest size, after which they are predominantly sold to meet the demands of the domestic half-shell market.

In 2021-22 Tasmanian farmers produced approximately 2,833 tonnes of oysters, around a third of the total Australian production of 9,011 tonnes (ABARES, 2022). By comparison, the global oyster aquaculture sector produced more than 6 million tonnes in 2020, which is 8.9% of total marine aquaculture production volume (FAO, 2022). A strong domestic demand for oysters is illustrated by the high volumes of imported oysters consumed in Australia, with over 8,000 tonnes of frozen oysters from New Zealand in 2022 (Seafood NZ, 2022). Conversely approximately 1% of domestic production volumes are exported, owing to the high domestic demand (Oysters Australia, 2020). Given the context of high global production levels and oyster market demand, the Tasmanian industry has a significant opportunity to expand its production. Access to productive farming areas, and greater efficiency in operations to enable cost-effectiveness will be key factors in harnessing this opportunity.

1.1.1. Overview of Pacific oyster farming practices in Tasmania

In Tasmania oyster production cycles rely on an intertidal farming component to produce a high-quality product for the half shell market (Figure 2). Due to the diversity in size and spatial area of different businesses, this can be achieved with several processes:

a) Intertidal Lease Operations

Oysters are exposed to air and UV during low tide and submerged during high tide. Intertidal farms utilise fixed and adjustable long-line systems, as well as fixed-height racks. Longlines have mesh plastic baskets suspended from horizontal lines, while mesh trays or baskets are secured within racks. The adjustable long-line system offers flexibility by enabling growers to modify oyster depth, immersion time, and exposure to environmental elements. This system enables oysters to feed during submersion, fostering growth and filter-feeding during high tide. The intertidal environment provides a natural setting for development of robust shells and meat condition with the balance of air exposure and immersion;

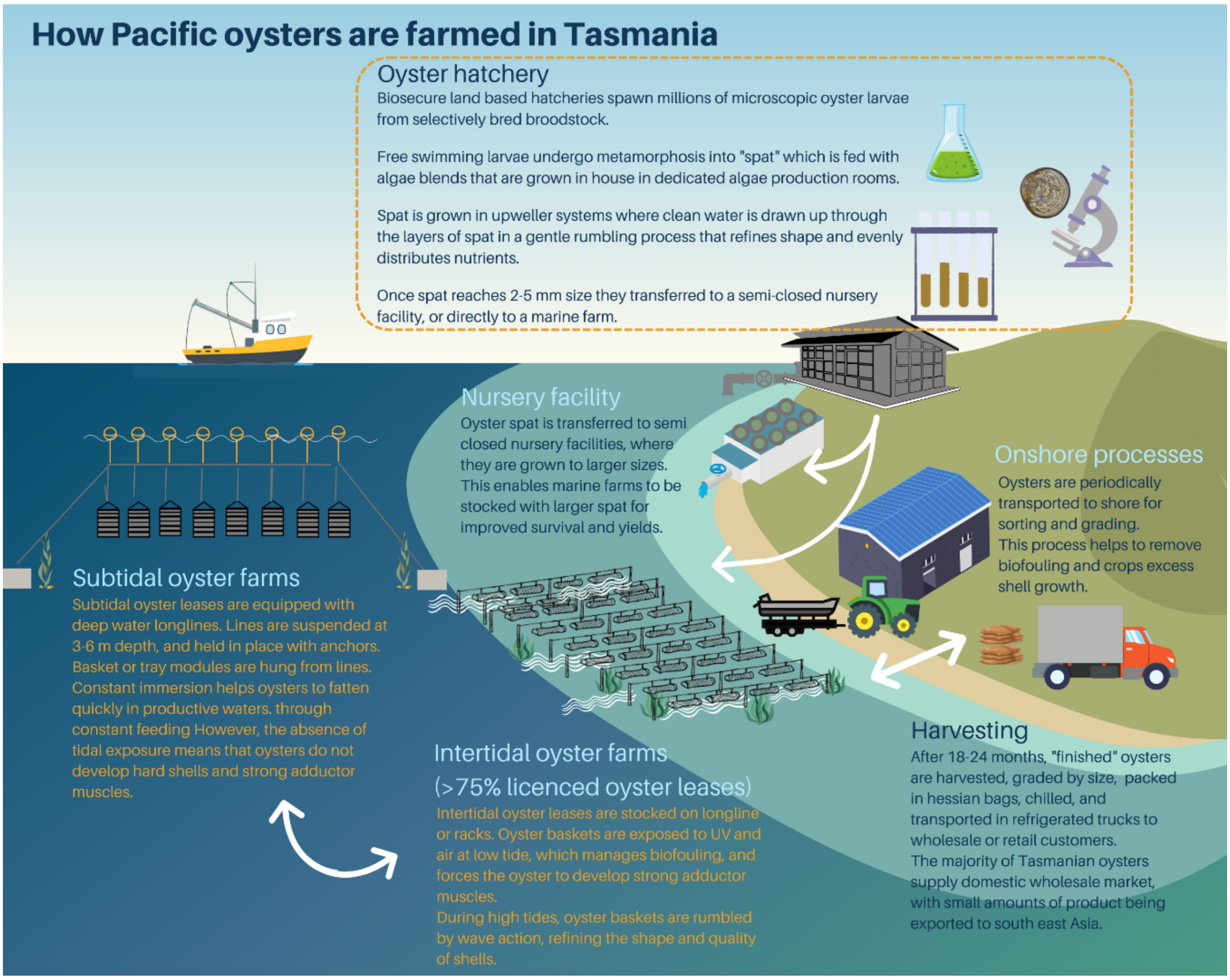
b) Intertidal and Subtidal Lease Operations

In this approach farmers operate on separate intertidal and subtidal leases, using a rack or longline method in the intertidal lease and a fully submerged longline in the subtidal lease. Submerged longlines consist of baskets or trays stacked in modules and suspended from lines at depths of 3-6 m. Growers translocate stock between the two; relying on the intertidal exposure to develop shell strength, shape, manage meat to shell ratio, and adductor muscle strength, then capitalising on the continuous feeding capacity associated with constant submergence on the subtidal lease; and

c) Subtidal Lease Operations

In scenarios where only subtidal leases are available, adaptable farming systems are required due to the absence of aerial exposure. To compensate, an artificial subtidal exposure is created using surface raft/lines that expose oyster baskets to air, UV, and wave action. The relatively recent innovation of the FlipFarm system is designed to replicate the intertidal aerial and UV exposure to manage fouling, as well as increase efficiency through semi-automated basket retrieval. This approach addresses the absence of natural intertidal conditions in subtidal lease operations.

Oysters are handled and graded throughout the production cycle with the aim of achieving the required shape ratio. The frequency of grading varies according to the environmental conditions of areas. Local environmental conditions can affect growth rates, uniformity of growth, and have varying severity of fouling, which all influence the frequency of grading events (Cassis et al., 2011). Handling also improves visual shell quality by preventing biofouling from attaching to the shell. Shell shape is also affected by the rumbling of oysters inside baskets, trays, or bags when they are exposed to wave energy, resulting in a deeper cupped shell (Brundu, 2020). This is achieved through the rumbling action abrading or "cropping" new growth around the margins of the shell (Thomas et al., 2019). The intertidal longline and basket systems used in Tasmania are designed to harness energy from tides and waves to achieve desired shell depth. When relying entirely on deep-water leases to grow oysters for the half shell market, floating or artificial intertidal conditions have demonstrated efficacy for finishing, and have been observed to result in greater shape uniformity in the cohort (Thomas et al., 2019).



How Pacific oysters are farmed in Tasmania

Oyster hatchery

Biosecure land based hatcheries spawn millions of microscopic oyster larvae from selectively bred broodstock.

Free swimming larvae undergo metamorphosis into "spat" which is fed with algae blends that are grown in house in dedicated algae production rooms.

Spat is grown in upweller systems where clean water is drawn up through the layers of spat in a gentle rumbling process that refines shape and evenly distributes nutrients.

Once spat reaches 2-5 mm size they transferred to a semi-closed nursery facility, or directly to a marine farm.

Nursery facility

Oyster spat is transferred to semi closed nursery facilities, where they are grown to larger sizes. This enables marine farms to be stocked with larger spat for improved survival and yields.

Onshore processes

Oysters are periodically transported to shore for sorting and grading. This process helps to remove biofouling and crops excess shell growth.

Subtidal oyster farms

Subtidal oyster leases are equipped with deep water longlines. Lines are suspended at 3-6 m depth, and held in place with anchors. Basket or tray modules are hung from lines. Constant immersion helps oysters to fatten quickly in productive waters. through constant feeding However, the absence of tidal exposure means that oysters do not develop hard shells and strong adductor muscles.

Intertidal oyster farms (>75% licenced oyster leases)

Intertidal oyster leases are stocked on longline or racks. Oyster baskets are exposed to UV and air at low tide, which manages biofouling, and forces the oyster to develop strong adductor muscles.
During high tides, oyster baskets are rumbled by wave action, refining the shape and quality of shells.

Harvesting

After 18-24 months, "finished" oysters are harvested, graded by size, packed in hessian bags, chilled, and transported in refrigerated trucks to wholesale or retail customers.
The majority of Tasmanian oysters supply domestic wholesale market, with small amounts of product being exported to south east Asia.

Figure 2. Schematic for process of farming Pacific oysters in Tasmania.

1.1.2. Current industry limitations that could be mitigated by offshore farming

Limits on intertidal space has driven a global trend for oyster industries to consider viability of operations in deeper, higher energy waters. For example, oyster production in Europe has steadily decreased since 1998, partly due to competition for space (Wijsman et al., 2019). In France where oyster aquaculture is heavily established in intertidal estuaries, the competition for space between farms and risk of urban runoff contamination has led to numerous investigations into relocating farms further from the coast (Barillé et al. 2020; Palmer et al. 2021). Spatial limitations, which have led to stagnated oyster yields and conflict over available space, has sparked an industry-wide restructuring in France. This restructure has prompted a reassessment of management practices and existing leases, with a particular focus on evaluating the suitability of nearshore sites (Barillé et al. 2020). The food safety concerns faced in Europe, Asia, and the US because of pollutant runoff are more severe than Tasmania and this is reflected in more restrictive harvest practices (Lowther et al., 2012, Dumbauld et al., 2009, Burket et al., 2018). Nevertheless, the Tasmanian Pacific oyster industry has similar vulnerabilities and limited scope to expand production due to spatial constraints.

The Tasmanian coastline features a relatively small proportion of estuarine water suitable for current oyster farming practices. Within the more productive estuarine waters there is limited scope to increase the current areas licensed due to competing community interests and current farming leases are most commonly at production capacity. Those waters that are leased and not currently farmed are typically quite depauperate and are either not viable or have marginal farming potential. This represents the major constraint for the expansion of the Tasmanian industry Given this consideration, some growers are already investigating the potential of deeper and more exposed locations. However, they encounter significant obstacles since existing farming technologies are inappropriate for even more exposed nearshore sites. With the appropriate technology, offshore farming could provide a definitive solution to this spatial limitation.

Regulatory closures due to pollution and harmful algal bloom (HABs) place further constraints on the current farming areas, often greatly impacting delivery of product to the market and placing greater demand on the areas that remain open. Farms located at closer proximity to pollution sources are at greater risk of prolonged closures. Many farming areas receive runoff pollution from significant land catchments, and/or are located near urban areas where sewerage spills occur. Presently, farmers have little scope to respond or act pre-emptively to such events by moving stock to avoid closures as current estuarine sites are often at capacity or the logistical constraints are prohibitive. Offshore sites are innately more distant to such pollution sources and if developed in an appropriate proximity to current estuarine operations and may offer much greater stock movement capacity to mitigate this problem. Likewise, when HABs occur the closures can be very protracted and widespread nearshore, and moving stocks to nearby offshore sites could help circumvent this problem. An offshore stock movement strategy holds potential for enhancing the overall resilience and sustainability of oyster farming in Tasmania, addressing challenges posed by regulatory closures.

During the review process, the Project Team engaged with key stakeholders within Tasmania's oyster industry, including representatives from the Oysters Tasmania board and the RD&E Sub-Committee. This also involved 20 participants from 13 oyster farming businesses, including the three major oyster producers in Tasmania. Industry stakeholders articulated the potential advantages of offshore expansion, underscoring expanded spatial availability, diminished usage conflicts, and potential improvements in water quality due to increased separation from pollution sources. Furthermore Additionally, stakeholders highlighted notable challenges including the lack of comprehensive understanding regarding primary aquatic productivity and localised hydrodynamics. A particular concern centred on the potential for suboptimal growth and condition in comparison to established inshore sites. These factors lead to uncertainty on return on investment considering the significant developmental expenses linked to offshore expansion. Other concerns raised included the need for enhanced efficiency in farming procedures, and restricted access to the land base facilities and infrastructure required to operations. The consultation revealed a consensus that the limited utilisation of high-energy leases was a significant factor hindering the industry's growth.

It is critical to Tasmanian oyster farming industry that any expansion to offshore farming be developed as a stepwise transition. This transition should commence with a focus developing farming techniques for exposed nearshore sites that are available for farming but underutilised. A parallel investment in developing true offshore framing techniques should be undertaken at the same time, but at on a smaller scale. The intermediary step would be the full utilisation of existing exposed nearshore sites, such as those in Great Oyster Bay, the Tasman Peninsula, and D'Entrecasteaux Channel. The full development of these sites will require considerable investment, and understanding of site locations and development of technology, but should position the industry for transition into the concluding step to true offshore farming, dependent of the success of the nearshore exposed site developments.

2. Methodology

The project commenced with an extensive literature review on multiple topics related to offshore oyster aquaculture. This review included peer reviewed and grey literature on offshore environmental conditions, and oyster aquaculture practices. Search terms of "offshore oyster aquaculture", "high-energy oyster aquaculture", "open sea oyster aquaculture", and "offshore IMTA" were initially used, however due to limited published research on the topic, a "backward snowballing" method was used to identify additional articles of relevance. The literature review aided in separating the project areas of consideration into biophysical factors and site selection, operational factors, and economic factors.

The project team organized theme meetings for the team of experts that were open for participation by interested oyster farmers. The two meetings were separated into Day 1: operational and economic factors, and Day 2: biophysical factors, aligning with the topics identified in the literature review. Meetings served as a platform for collaboration and knowledge exchange. This interactive process allowed integration into the project of practical knowledge from industry stakeholders.

The feedback received from the attendees were considered in refining the project's objectives and research focus. This continuous dialogue between the project team and farmers aimed to ensure that the project addressed real-world challenges and needs.

3. Review of Previous Research

3.1. A brief review of global approaches to offshore oyster farming

Countries in Europe, Latin America and Oceania are considering expanding oyster production by offshore farming, driven by a similar theme of needs. Economic potential and climate change are big drivers in New Zealand's offshore shellfish research (Heasman et al. 2020) with NZD $16.8 million in total awarded by the New Zealand Ministry of Business, Innovation and Employment over the past decade. Offshore oyster aquaculture is also being explored in several counties in Europe, driven by the demand for high quality European seafood products, and the effects of declining water quality and spatial limitations impact inshore production. Through the 2010s there were project activities funded through EU HORIZON 2020 innovation grants to support development, the funding specific to oyster aquaculture projects totalled over €2.9 million. One of the focal points of the European investment was the aim to demonstrate feasibility of multi-use platforms (i.e., energy production and aquaculture). The collaboration involved commercial partners including clean energy producers, Parkwind and Jan De Nul Group, maritime company Brevisco, and supermarket group Colruyt.

Research and development efforts conducted overseas spanned various categories, reflecting both the complexity of the subject and the maturity of the respective industries involved. These research initiatives have focused on developing culture systems designed for high-energy marine environments and tested oyster performance and husbandry methods. Additionally, significant attention has been directed towards understanding and enhancing spatial planning. The expansion of oyster aquaculture into new locations and effectively managing shared spaces with other activities have presented a multifaceted challenge prompting research and investment.

3.1.1. New Zealand

The Cawthron Institute, backed by an NZD $5.9 million investment from the New Zealand Government, initiated a five-year project titled “Novel farming systems enabling multiple shellfish species culture in open ocean sites" aimed at boosting the growth of shellfish aquaculture in open ocean locations (NZ Ministry of Business, Innovation & Employment, 2016). Following this initial venture, an additional infusion of $10.9 million in funding was secured over five years to continue progress and commercialisation through a project titled is “Ngā Punga o Te Moana: Anchoring our Open Ocean Aquaculture Future” (NZ Ministry of Business, Innovation & Employment, 2021). This financial support has facilitated the creation of an experimental high-energy farm located 11 km off the coastline in the Bay of Plenty. While this project marked the development of farming equipment, a prior investigation into aquaculture site suitability in the Bay of Plenty ran from 2003 – 2007, during this period researchers collected extensive data on currents, waves, wind, biofouling, phytoplankton and available seston, water quality parameters, and seasonal variation in site conditions (Cheney et al., 2010). In July 2018, a telemetered monitoring buoy was installed at the site, which provides continuous and detailed data on hydrodynamic conditions and water quality to Cawthron researchers. This data provided valuable real-time insights prior to the deployment of the experimental system.

A major output for this project is the development of the Shellfish Tower™; a hexagonally shaped submersible structure that is moored with a single line to a screw anchor in 45 m water depth (Figure 3.). The system has been trialled in an open ocean site 11 km off the Bay of Plenty with a depth of 50 m. (Heasman et al., 2021). The prototype system was tested in laboratory flume experiments to subject the system to extremes in current and wave energy. Results from these tests enabled researchers to identify weaknesses and highlighted monitoring and modelling considerations for field deployment (Landmann et al., 2021). The prototype system that is currently deployed is durable, withstanding significant wave heights of 4.6 m, and having the design features to work with the energy of the currents, such as two swivels through the mooring line designed to counter the twisting forces from currents. Investigators concluded that at the time of reporting, the prices fetched for high quality oysters and scallops are of sufficient value to justify the cost of this novel farming system (Heasman et al., 2021). Initial production performance trials were disrupted by COVID-19, preventing the recording of systematically collected growth data, nevertheless researchers reported promising initial results for future trials, with oysters growing from 1.5 mm to 99 mm in 10 months (Heasman et al., 2021).

Currently, within the Cawthron Institute project, triploid Pacific oysters are being grown in the Bay of Plenty site at a depth of 9 m. The oysters were seeded at 6 mm into baskets in May 2023 and the growth to date has been very promising. It is expected that this cohort will be harvested between May and August 2024. Further growth trials considering stocking densities and seeding dates will be initiated shortly. Based on the success to date, new Shellfish Towers™ are being constructed to be placed at two sites, one semi protected and one exposed (Heasman, 2023 pers. comm. 17 August).

3.1.2. Europe

The European offshore project titled UNITED has encompassed several sub-projects in collaboration with commercial partners, aiming to assess the feasibility of integrating oyster aquaculture and wind energy production (Van den burg et al., 2020). The project, due for completion end 2023 includes a multi-species aquaculture pilot project in the Belgian North Sea, co-located with offshore wind infrastructure (CORDIS, 2020). This project has followed a stepwise approach, starting with the trial of farming systems in a near-shore location 5 km off the Belgian coast throughout 2020. Subsequently, it transitioned to the operational phase, involving the installation of oyster longlines at the offshore wind farm located 48 km from shore in August 2022 (Nevejan et al., 2023)." The initial field trials demonstrated the production of high-quality finished oyster products. However, biofouling has been identified as a significant constraint to the success of this initiative (Colruyt Group, 2022). With offshore trials ongoing, the final determination of the cost benefits associated with this work is still pending.

While the UNITED project is an example of true open ocean experimentation, other European countries are exploring a transition out of the intertidal zone to deeper and higher energy near-coastal areas as a means of developing their industries. An EU HORIZON 2020 Innovation grant (€3.6 million) titled "AquaSpace" encompassed work that explored the expansion of shellfish cultivation areas beyond the near-coastal region in the Adriatic Sea along the eastern coast of Italy (Brigolin et al., 2017, Galparsoro et al., 2020, Bertolini et al., 2021). In this project the greatest barriers to development were identified as regulatory permitting, zoning/planning, and logistical feasibility of farming operations and transporting shellfish to market. Consequently, a spatial planning tool tailored for oyster and mussel production was developed to address these concerns and accelerate development of the new sites (Brigolin et al., 2017). A further EU HORIZON 2020 Innovation grant (€5.9 million) titled “TAPAS” had the objective of creating tools for the planning and assessment of sustainable aquaculture developments. Part of this project examined offshore oyster operations along the Atlantic coast of France, where inshore crowding and competition for space is the primary barrier to industry growth (Barillé et al., 2021). Similar conclusions to the AquaSpace project, in that regulatory and planning hurdles were recognised as major barriers to advancing development.

3.1.3. Chile

In Chile, expanding capability for bivalve aquaculture out of inshore sites has been previously identified as a research priority that has potential to unlock increased production capacity and profitability (Lovatelli et al., 2008; Diaz & Sobenes, 2022). Both oyster and mussel aquaculture have been identified as having high potential for growth within the Chilean industry (FAO, 2018). Research is still in its infancy, with a recent study comparing growth performance of Pacific oysters using different types of culture equipment in a high energy site vs traditional low energy site being the first of its kind (Diaz & Sobenes, 2022). This work has demonstrated favourable growth performance for oysters deployed at a high energy site, vs a control treatment deployed in a sheltered location on identical culture equipment.

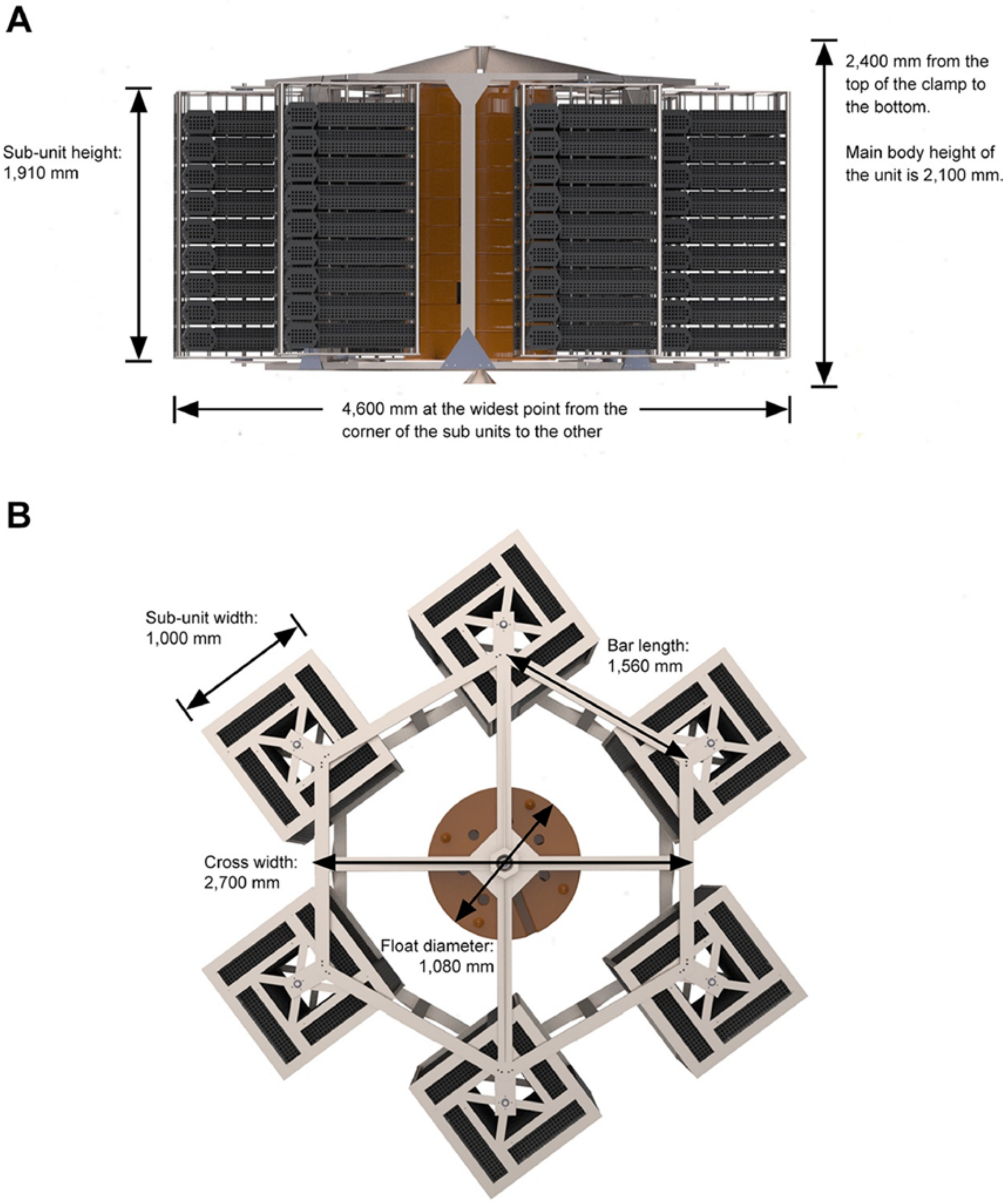


Figure 3: Design and dimensions of the Shellfish Tower™ showing side view (A) and top-down view (B) from Heasman et al., 2021.

3.2. Biophysical feasibility of offshore oyster production

A specific set of biophysical characteristics are needed at offshore sites to underpin the fundamentals of oyster farming, yielding adequate oyster growth, survival, and product quality; and providing a physically suitable environment for farming operations. Fundamentals to the farming needs are clean water and adequate nutrients, with site hydrodynamics a governing factor for water quality and productivity. Additionally, the hydrodynamics significantly impact other biological factors, including the proliferation of harmful algae blooms (HABs), the occurrence of biofouling, and disease (Figure 4). Hydrodynamics also encompass the key physical considerations as currents and wave action can affect the performance and stability of aquaculture structures.

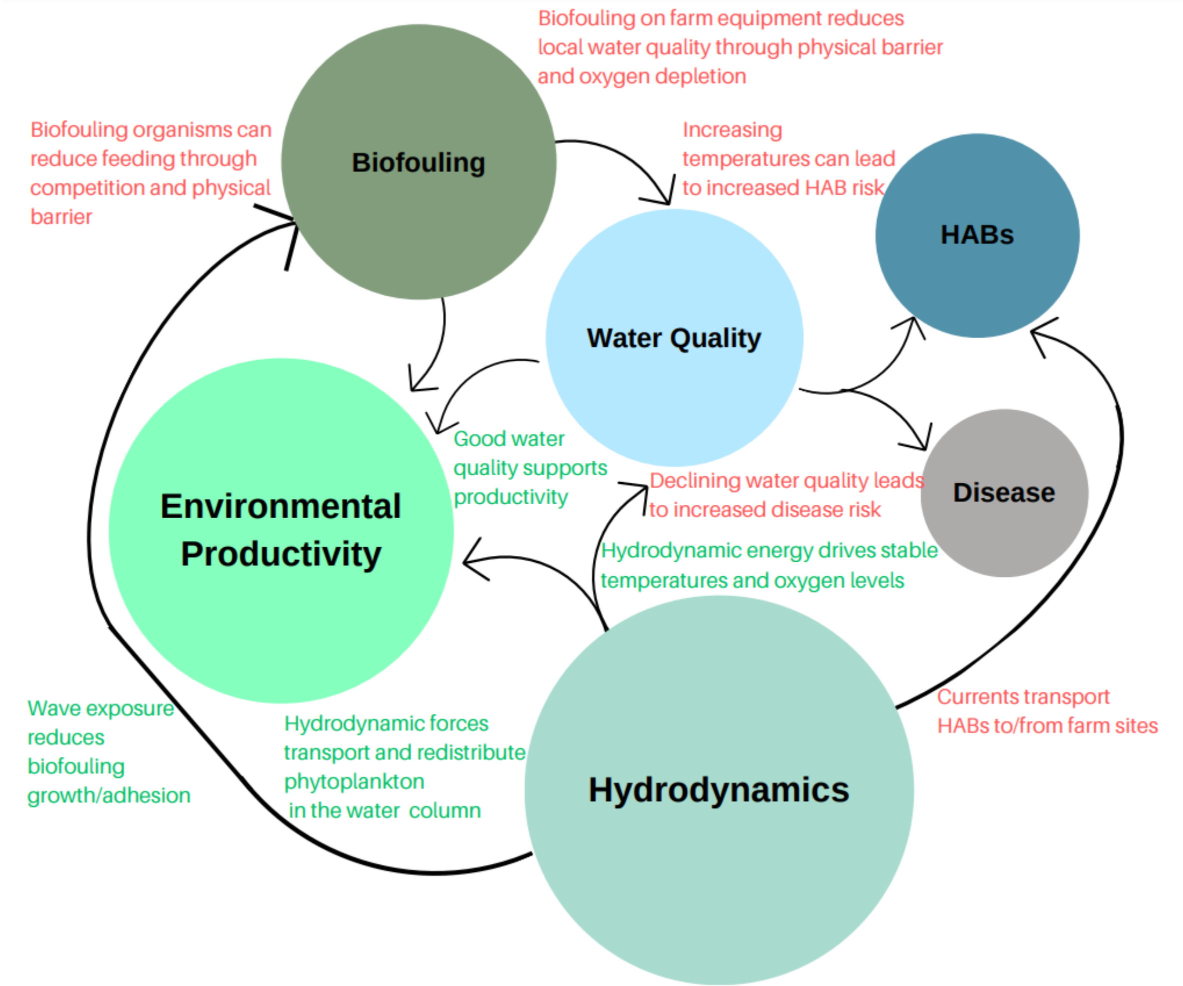


Figure 4. The interaction between various environmental factors that need to be considered for offshore oyster aquaculture.

3.2.1. Hydrodynamics

The hydrodynamics of a potential aquaculture site play a pivotal role in determining its suitability for oyster farming and have a flow on influence on various other biophysical factors. Offshore locations are exposed to significantly stronger hydrodynamic forces compared to inshore sites, as such careful consideration need be applied when implementing farming systems in higher energy areas (Huang et al., 2020). Robust farm equipment such as lines, cages, floatation, and moorings are imperative in areas with high energy currents and waves (Jimenez-Martinez, 2021). This choice naturally leads to higher costs due to the necessity for enhanced structural strength. Therefore, when planning both the equipment and layout for offshore aquaculture sites, an in-depth understanding of the local hydrodynamics is critical to safeguard farmers investments.

In addition to damage or loss of equipment, wave-induced stresses also have potential to impact the growth of oysters (Campbell & Hall, 2019). Environments with high-energy wave activity expose oysters to various physical stresses, including turbulence from waves, collisions with solid objects, and sediment erosion (Lou et al., 2022). These forces may lead to shell damage, potentially impacting growth and survival. Prolonged exposure to high wave energy has been observed alter shell morphology; for instance, oysters subject to intense wave exposure tend to develop thicker, more compact shells (Pogoda et al., 2011). Incorporating an understanding of characteristics such as wave depths, heights, allows farmers to make appropriate choices regarding depth line and basket depth that can influence their finished product.

Hydrodynamic factors also hold the potential to foster favourable water quality, adequate food supply, and overall conducive conditions for oyster growth. Water circulation patterns, driven by currents, waves, and tides, influence the exchange of materials between the aquaculture system and the surrounding environment, impacting water quality and primary productivity (Chilton et al., 2021). Improved circulation in offshore locations is an attractive prospect for oyster farms, assuming adequate primary production in the waters (Cheney et al., 2010). High flow rates can enhance the removal of waste materials and elevate oxygen levels, facilitating higher stocking densities. In contrast, insufficient flow experienced in certain inshore sites hampers effective dispersion of food particles across the entire farm (Snyder et al., 2017). Inshore, shallow, low-energy estuarine locations may also experience increased sediment deposition, modifying the benthic environment and biodiversity (Gallardi et al., 2014).

3.2.2. Water quality

In oyster aquaculture, water temperature, dissolved oxygen, and turbidity are important environmental requirements that influence oyster growth and overall productivity of operations. Water quality is a key consideration as there are distinct differences in range and variability when comparing inshore and offshore sites. In instances where water quality parameters become limiting to oysters, the overarching factor is often the proximity of a site to land run-off and eutrophication influences (Knapp, 2013). In this context, offshore sites can offer a security against water quality issues. Increased water exchange and flow rates in more exposed areas help to regulate localised water temperature, and oxygen.

Pacific oysters demonstrate wide temperature tolerance, with a growth range of 13-27 °C with intertidal areas in Australia experiencing wide temperature fluctuations due to weather conditions and tides (Bayne, 2017; Pathirana et al., 2022). Despite this wide tolerance, extended periods of high temperatures are often associated with mortality events, with the risk factor increasing with eutrophication or oxygen limitations (Malham et al., 2009). To mitigate risk, farmers can relocate stock to deeper areas for increased submergence time or avoid handling during periods of high temperatures, albeit with potential limitations on farm productivity. The more stable water temperatures experienced in offshore sites can contribute to less complicated farm management in warmer months. Temperature also effects dissolved oxygen with oxygen saturation decreasing as temperature and salinity increases (Bougrier et al., 1995). Adequate dissolved oxygen is essential for several physiological functions, including energy production, nutrient assimilation, and waste removal (Wilson & Burnett, 2000). Inshore and estuarine areas are vulnerable to low oxygen due to potential eutrophication from land runoff as well as higher temperatures (Cloern, 2001). With this combination of factors, dissolved oxygen can be limiting to oyster farm productivity.

Turbidity is another key water quality factor, which refers to the cloudiness or haziness of the water caused by large numbers of suspended particles. High turbidity can reduce light penetration, leading to a decrease in the depth of the photic zone, direct implications for photosynthesis and algal production (Cloern, 1987). In addition, high turbidity levels are associated with high particulate loading, which has been linked with reduced oyster filtration and growth in inshore areas (Snyder et al., 2017), and associated with comparatively improved growth in offshore areas (Barille et al., 2020).

3.2.3. *Harmful algal blooms*

Harmful algal blooms (HABs) are an important consideration when selecting farm sites as they have significant implications for food safety and market access. It is imperative to develop a comprehensive comprehension of HAB risk factors in new and oceanic locations. A HAB refers to the rapid proliferation or excessive growth of specific species of microscopic algae in aquatic environments (Lenzen et al., 2021). Although the species responsible for HABs are inherent components of the marine ecosystem, the intensification of bloom formation can be attributed to heightened nutrient availability and reduced water column mixing due to diminished wind, wave, and current-driven flows. While not all algal blooms are harmful, certain blooms have the capacity to synthesize toxins that impose substantial risks upon human health, marine organisms, and overall ecological integrity.

Algae that form HABs produce biotoxins that can accumulate in the tissues of shellfish, such as oysters, clams, and mussels, making them unsafe for human consumption. If affected shellfish are consumed, it can result in paralytic shellfish poisoning, amnesic shellfish poisoning, diarrhetic shellfish poisoning, and neurotoxic shellfish poisoning, causing illness and in severe cases, death (FAO, 2004). The presence of biotoxins in oysters not only poses serious health risks but also carries significant economic repercussions. In some cases, government regulators may close shellfish harvesting areas during a HAB event to protect public health (McGillicuddy et al., 2003). This can have significant economic impacts on shellfish producers and the surrounding communities that rely on shellfish harvesting as a source of income. In Massachusetts, a PSP outbreak resulted in substantial economic losses estimated at $12 to $20 million with additional impacts being observed in additional areas of New England (NOAA, 2017; Farabegoli et al., 2018). According to a study conducted by Martino et al. in 2020, a mere 1% shift in the biotoxin levels has a significant impact on shellfish production, resulting in a decline of approximately 0.66%. They found this to lead to an annual reduction of 1,080 tons (equivalent to 15% of the total production) and an economic loss of £1.37 million per year.

The impact of HABs are also felt locally. In 2012, Alexandrium catenella (a highly toxic dinoflagellate), was initially observed off the eastern coast of Tasmania. Subsequently, these occurrences have led to instances of human paralytic shellfish poisoning and prolonged shutdowns (lasting up to 25 weeks) of mussel, oyster, and other shellfish industries (Condie et al., 2019). The shutdowns are often prolonged even following the end of a HAB as the oysters depurate toxins from their tissues (Gibble et al., 2016).

3.2.4. *Disease considerations in Pacific oyster farming*

Disease often significantly impacts aquaculture production across all sectors (Bondad-Reantaso et al., 2021). Its impact on production yield, product quality, and economic viability underscores its significance in the aquaculture industry. Globally, there has been an increasing frequency of disease impacts on oyster production caused by a range of pathogens (Arzul et al., 2017; Zhang et al., 2023). Notable examples affecting Tasmanian industry include Ostreid herpesvirus-1 microvariant (OsHV-1 µVar), the pathogen causing of Pacific Oyster Mortality Syndrome (POMS), Vibrio parahaemolyticus, and Polydora websteri, commonly referred to as mudworm.

Pacific Oyster Mortality Syndrome has emerged as a serious threat to Pacific oyster aquaculture on a global scale. In January 2016, a POMS event caused a mortality rate of 78% in commercially important estuaries in southeastern Tasmania (de Kantzow et al., 2017). Selective breeding has achieved some POMS resistance; however, the disease is amplified by environmental factors, notably during periods characterised by high temperatures and higher tidal ranges (Delisle et al., 2022). The high mortality caused by POMS inflict significant economic losses and given the implications of this risk, it is imperative to thoroughly address risk mitigation within the scope of any offshore developments. Temperature variations and water quality parameters play crucial roles in disease outbreaks and their consequences, including POMS (Delisle et al., 2020). Extreme temperatures can create favourable conditions for pathogen proliferation and virulence, resulting in heightened disease prevalence and severity. Similarly, variations in water quality, encompassing dissolved oxygen levels, salinity, and nutrient concentrations, impact oyster health and immune response, increasing their susceptibility to diseases (Soletchnik et al., 2007). Understanding these complex relationships is vital for implementing effective disease management strategies and ensuring the sustainability of offshore oyster production (see Section 4.1.2).

Bacterial pathogens, particularly those within the Vibrio genus, have been implicated in widespread mortalities that affect different life stages of Pacific oysters (Petton et al., 2015). In addition to its pathogenicity for oysters, Vibrio parahaemolyticus poses a significant risk to human health. Various pathogenic strains are associated with causing symptoms of gastroenteritis if contaminated oysters are consumed (FAO/WHO, 2011). Increasing prevalence of Vibrio infections thought to be traced back to seafood is a concern for public health officials and complicates risk management practices (Hedges, 2022). Like POMS, Vibrio is associated with elevated temperatures experienced in shallow intertidal estuaries, which further complicates management considering changing climate (Baker-Austin et al., 2017). More stable (lower) offshore temperatures may have the potential to mitigate the impacts of this disease.

3.2.5. Biofouling

Biofouling refers to the accumulation and colonisation of living organisms, such as algae, barnacles, and mussels, on submerged surfaces, leading to the formation of unwanted biological growth, causing operational challenges in various industries, including aquaculture (Delgado et al., 2023). The oyster industry faces a notable challenge due to the presence of biofouling, resulting in substantial costs dedicated to biofouling control, with approximately 14.7% of annual operating expenses allocated to this purpose (Adams et al., 2011; Lacoste & Gaertner-Mazouni, 2015; Sievers et al., 2019). Apart from the significant cost of additional husbandry, biofouling can impede water flow and oxygen supply, increase drag on farming structures, and disrupt the feeding and growth processes of oysters (Fitridge et al., 2012; Archana et al., 2019).

To manage biofouling, various strategies have been employed, including chemical treatments, physical barriers, biological control, and mechanical cleaning (Sievers et al., 2019). Chemical treatments involve the use of antifouling paints that can harm the environment and require regular reapplication. Physical barriers, such as screens or mesh, can prevent the attachment of marine organisms to aquaculture structures but may interfere with water flow and require frequent maintenance (Hopkins et al., 2021). Biological control entails introducing predators or competitors of fouling organisms, which may have unintended ecological impacts. Mechanical cleaning involves the physical removal of fouling organisms from aquaculture structures. Manual cleaning, which remains the most employed control measure and shellfish structures, is a labour-intensive and costly strategy (Adams et al., 2011). Recent innovations such as FlipFarm have been developed to operationally manage biofouling through exposure to air and UV. The air-drying works effectively to manage biofouling, though the system is not directly transferrable to high energy environments now.

The impact of biofouling is particularly pronounced in subtidal farms, as the equipment lacks the natural exposure to tides that aids in the elimination of fouling organisms. Future offshore oyster farming will face similar biofouling problems to those experiences by current subtidal oyster operations, and management of biofouling will be a major component in developing offshore oyster cultivation.

3.2.6. Environmental productivity

Changes in ocean currents can impact the quality and quantity of phytoplankton and other food sources available to the oysters. Oysters are filter feeders, feeding on phytoplankton, detritus, and organic matter suspended in the water column. Availability of food would be an essential site selection criterion for offshore oyster aquaculture. Research has suggested that oysters may preferentially feed on phytoplankton species with more optimal fatty acid profiles (Muniz et al., 2019).

Food availability in offshore locations is estimated using chlorophyll-a measurements as proxy for phytoplankton abundance (Davies et al., 2018). The validity of chlorophyll-a measurements should be considered when drawing comparisons to inshore/estuarine food availability, as other food sources are of significantly increased importance in inshore environments (Cheney et al., 2010). The total organic matter can be made up of detritus, bacteria, and dead phytoplankton contributes significantly to productivity (Barillé et al., 1997). So, while chlorophyll a concentration may be a good indication, it is not the whole picture. As aquaculture sites move further offshore, phytoplankton biomass increases in importance as the primary food source. River plumes, especially in flood conditions, have been demonstrated to transport sediments, nutrient, and dissolved material large distances from shore (Fredston-Hermann et al., 2016). The extent that Tasmanian offshore sites are affected by river plume nutrients would provide valuable insights from which to build our understanding on total available seston for offshore oyster farms. Another factor to consider is the seasonality of phytoplankton blooms and feed supply offshore as it may have heavy implications on capacity to supply harvest quality product to the market. The transportation of nutrients from the open sea is influenced by two primary dynamic factors: upwelling, which involves the transfer of nutrients from deeper waters to the euphotic zone, and water exchange characterised by cross-shore advection (Lü et al., 2010; Wei et al., 2010; He et al., 2022).

3.3. Methodology and considerations for site selection

Site selection is a critical step in the process of developing offshore oyster farming. Aquaculture proponents face the challenge of building an adequate understanding of the biophysical attribute and other characteristics of a potential site to make informed decisions. Challenges include the lack of data for new sites, especially regarding food availability and seasonal patterns in conditions and productivity. Even with available data, operators might encounter challenges in interpreting data effectively for purposes such as production planning and the creation of oyster growth models, which are vital for conducting cost-benefit analyses. An additional hurdle involves the logistical aspects of establishing an offshore oyster farm. A location boasting favourable conditions could still pose challenges in terms of convenient land access or nearby boat ramps. Such challenges may increase transportation expenses and time investments, thereby diminishing the feasibility of offshore operations.

3.3.1. Data availability and limitations for site selection

Historical and broadscale weather and oceanic data such as weather patterns, wind speeds, wave heights, and storm frequency is readily available and can provide insights into the conditions and potential risks of a site. Similarly, widespread mapping of environmental productivity can be projected using chlorophyll-a content from satellite imagery estimations (Snyder et al., 2017, Brigolin et al., 2017, Palmer et al., 2020, 2021). This broad scale data is a useful indicator in initial establishment of potential site candidates, but it may lack the detail to capture local variations in environmental conditions and will likely require a level of validation from in-situ sensors or monitoring buoys.

Until recently the Tasmanian oyster industry's access to in-situ water quality data was limited and sporadic. Oysters Tasmania's Sensor Network and ShellPOINT data portal that has been installed in Tasmanian oyster growing areas in 2022-23 will enable farmers to access real time temperature, salinity, and tide data in lease areas. This technology has been implemented to assist in managing food safety by identifying periods of elevated contamination risk from freshwater run-off, and Vibrio contamination during high temperature, prompting more agile response for mitigating risk.

The collection of environmental data in Tasmanian offshore sites is a necessary step in investigating development potential. The investment in monitoring of environmental conditions preceded field trials and development for the offshore oyster research in New Zealand, whereby the environmental data informed location feasibility for offshore farming, as well as design and development of experimental equipment (Heasman et al., 2020, Landmann et al., 2021).

3.3.2. Environmental monitoring

Environmental monitoring technologies are essential to build data to support the understanding of the biophysical status of potential offshore farming sites for site selection, to evaluate the suitability of farm systems, and the growth and health of oysters. Remote monitoring technologies will be of relevance to offshore developments considering the greater distances from shore and harsh conditions (Table 1). Effective monitoring systems for weather and wave conditions allow farmers to make informed short-term decisions around the timing of maintenance and harvesting plans at offshore sites, and salinity and temperature data can aid in simplifying harvest planning and compliance. Climate monitoring data can be applied as an indicator of disease risk. In an offshore setting where day to day visual inspection of stock is less feasible, it becomes important to identify periods of heightened risk that prompt a site inspection. This may be in the form of temperature and dissolved oxygen data from sensors, or satellite imagery (Table 1). The surveillance of long-term trends in the environment, such as seasonal temperature changes, chlorophyll-a levels, and occurrence patterns of harmful algal blooms, feeds into production and operational strategies for the farm site or sites. Given the expected greater financial investments in offshore ventures, the ability to simulate production cycles becomes critical for input into cost-benefit analyses and calculating the return on investment. During the development and field testing of offshore farming equipment, monitoring technologies will be valuable for drawing conclusions on the capability, efficacy, and limitations of designs. For example, routinely assessing the severity of biofouling will be an important for prospective sites and novel farm systems. Similarly, monitoring ocean conditions plays a key role in defining success and/or physical limitations for new farming equipment.

Table 2: Monitoring considerations, technologies, and environmental variables for offshore oyster aquaculture operations.

Monitoring	Considerations	Technology/ Methodology	References
Climate monitoring	- Ocean temperature/local water temperature - salinity, - dissolved oxygen levels, - ocean currents	- Temperature loggers - Sensors: Conductivity & salinity meters, dissolved oxygen sensors, current meters	Smith, & Johnson, 2010; Gu *et al.*, 2022; Lu *et al.*, 2022

Monitoring	Considerations	Technology/ Methodology	References
Biofouling	- Assessment of the accumulation of organisms on surfaces	- Routine visual inspections of farming equipment to assess for level of biofouling - Biofouling sensor technology	Delgado *et al.*, 2021; Hopkins *et al.*, 2021; Wu *et al.*, 2023
Nutrient Productivity	- Monitoring quality and quantity of phytoplankton and other food sources available to the oysters. - Monitoring the development and movement of harmful algae blooms (HABs)	- chlorophyll-a assay using a spectrophotometer - Laboratory analysis of meat and water samples for biotoxins and harmful algae species - Satellite imagery - Remote sensing techniques	Burrell *et al.*, 2016; Dillion *et al.*, 2021; Lin *et al.*, 2021; Newell *et al.*, 2021; Maradhy *et al.*, 2022
Disease	- Monitoring for disease outbreaks	- Regular monitoring of oyster health through visual inspections and sampling - Use of molecular diagnostic tools, such as polymerase chain reaction (PCR) assays, to detect the presence of pathogens in oyster tissue or water samples - eDNA based analysis for monitoring pathogens in the water column	Dulić *et al.*, 2019; Bohara *et al.*, 2022; Ubina & Cheng, 2022; Volpe *et al.*, 2023

3.3.3. Established models that can be applied to site selection

Various growth models have been developed as effective tools for evaluating the potential suitability of different sites using environmental data. These models facilitate a comparative analysis of productivity levels among different locations and could provide valuable insights for site selection and farm development. It is important to note, however, that the applicability of these models to high energy sites may be limited, as they were initially developed for sheltered areas. The subsequent sections review the specifics of such models, which include the FARM Model, the Dynamic Energy Budget (DEB) model and the Shellsim Model.

3.3.3.1. Chlorophyll a

The Chlorophyll-a model utilises various data sources, including satellite imagery, in-situ measurements, and environmental parameters such as water temperature, light availability, and nutrient concentrations, to estimate the spatial and temporal distribution of chlorophyll-a in a water body (Palmer et al., 2020; Gernez et al., 2017; Armono et al., 2021). By quantifying chlorophyll-a concentrations, the model helps researchers and environmental managers assess the health and productivity of potential aquaculture sites, detect changes in phytoplankton biomass, and identify areas of potential concern, such as algal blooms or nutrient pollution. In offshore settings, chlorophyll-a is important for modelling the abundance of phytoplankton blooms, which serve as a food source for oysters. Chlorophyll-a data can be applied in identifying broad scale trends in phytoplankton blooms using satellite imagery to inform site selection. In more localised applications, chlorophyll-a data can assist farmers to better understand where in the water column phytoplankton is abundant to inform optimal stocking depth (Mizuta & Wikfors, 2019a).

3.3.3.2. FARM Model

The Farm Aquaculture Resource Management (FARM) model is a comprehensive tool that serves the interests of both farmers and regulators, encompassing three primary purposes: (i) conducting prospective evaluations of suitable culture locations and species selection, (ii) optimising ecological and economic aspects of culture practices, including determining optimal timings and sizes for seeding and harvesting, as well as densities and spatial distributions, and (iii) assessing the environmental impacts associated with farm-related eutrophication effects, with an emphasis on potential mitigation strategies (Newell et al., 2019). These parameters encompass temperature, depth, chlorophyll a, particulate organic matter, total particulate matter, dissolved oxygen, current speed, farm area, farm design, layout, stocking density, and total input volume, including the number of individual animals and total biomass. Within studies, the FARM model has been employed to estimate the productivity of oyster farming sites, as well as to eliminate locations with low suitability (Ferreira et al., 2007; Silva et al., 2011). However, it is important to acknowledge that the FARM model has limitations in that it relies on static environmental input data, thereby neglecting seasonal fluctuations in environmental parameters.

3.3.3.3. ShellSIM model

The ShellSim model represents a computational framework used to simulate and forecast the growth and development patterns of shellfish, primarily focusing on bivalve species including oysters, clams, and mussels. Through the integration of key parameters such as temperature, food availability, water quality, and other factors, the ShellSim model enables the optimisation of aquaculture practices, projection of growth rates, and assessment of the potential consequences of fluctuations in environmental conditions on shellfish populations (Hawkins et al. 2013). This model has been employed to simulate the adverse growth effects of elevated particulate matter in inshore areas and to pinpoint potential farm sites (Newell et al., 2021). The model successfully projected meat weights comparable to field production measurements and produced similar outcomes for satellite-derived food source inputs (chlorophyll-a and particulate organic matter) compared to measurements of actual food inputs. The ShellSim model was validated against field trials that compared oyster performance across various suspended culture methods at two Italian lagoon sites. The model exhibited strong growth predictability, achieving the closest fit when incorporating multi-criteria feed sources and customized environmental conditions (Graham et al., 2020). While specific data pertaining to offshore locations is currently unavailable, it remains evident that any ShellSim experimentation would be most effectively informed by in situ offshore environmental data.

3.3.3.4. Dynamic energy budget (DEB) model

Several models exist that elucidate the growth dynamics of molluscs in relation to environmental factors, such as temperature and food availability. One such model is the Dynamic Energy Budget (DEB) modelling approach, the parameters of which are well established for Pacific oysters (Pouvreau et al., 2006). This modelling framework has been adapted specifically to capture the intricate dynamics of growth and reproduction exhibited by the Pacific oyster in diverse geographical areas, encompassing controlled as well as natural conditions (Stechele et al., 2022). Dynamic Energy Budget models differ from net-production models in the way they utilise available energy for growth prediction. Net production models (such as FARM and ShellSim) allocate the available energy source primarily for maintenance, with the remaining portion dedicated to growth (Graham et al., 2020). In DEB models, energy acquired from food is initially stored in reserves, which are subsequently employed to support various metabolic processes, including maintenance, growth, development, and reproduction. DEB modelling becomes relevant when calculating cost/benefit analyses and production cycles for offshore sites, considering the expenses associated with maintaining maturation and how this impacts profitability and harvest continuity.

A notable application of DEB modelling was demonstrated by Palmer et al. (2021) in their investigation of the suitability of offshore sites for oyster aquaculture in Europe, considering climate change projections. The study identified several areas within Europe that were deemed as priority regions for the establishment of offshore Pacific oyster cultivation. To assess site suitability, historical satellite data encompassing sea surface temperature and chlorophyll concentrations were incorporated.

3.4. Operational factors

The success and efficiency of offshore oyster farming operations depend on various factors that encompass the entire operational framework. Offshore conditions carry greater complexities and will incur greater costs for equipment solutions. The increased durability and strength needed for farm systems to withstand the pressures of the biophysical environment is perhaps the most significant difference between inshore farm systems. In this section we will consider insights from overseas experimentation that may guide the direction of equipment selection and design within the Blue Economy CRC, albeit after building a thorough knowledge basis on the biophysical characteristics of Tasmanian offshore sites.

These conditions not only necessitate the need for robust farm systems, but also reduce the number of days that the farm may be accessed and worked. Reduced working days and greater travel distances means that offshore oyster farming operations will require highly efficient farming processes such as grading and harvesting. Offshore conditions also expose aquaculture to a greater risk of marine debris or equipment loss. This increases costs and comes with a risk of environmental and reputational damage. Accordingly, offshore farming equipment must be designed with durability in mind, but options for more readily recyclable plastics and biodegradable material is an important consideration. Access to infrastructure is critical to offshore operations. Farmers need access to suitable shore bases to run operations from, and for those not operating a waterfront base require boat ramps in proximity. If infrastructure is too remote, the increased travel time and distance will impact feasibility.

By understanding and optimising farm systems and production processes, offshore oyster farming has the potential to achieve highly efficient practices, sustainability, and overcome challenges associated with the harsh offshore environment.

3.4.1. Farming systems and equipment

In subtidal leases, which are the most like potential offshore sites, the inherent limitations arise from the inability of farmers to leverage natural low tide exposure to promote the development of shell hardness, shelf life through adductor muscle strength, and biofouling management. The oyster holding systems used in subtidal leases include, longlines, baskets, trays, or lanterns with some farmers opting for raft structures. The suitability of these types of systems in offshore sites is contingent upon local hydrodynamics, depth, bathymetry, as well as wave and wind conditions. When selecting or developing farm equipment, there are two key considerations: 1) ensuring the quality of the market product, and 2) guaranteeing the durability of the farm infrastructure, given the heightened exposure to currents, winds, and waves. Stocking density should also be considered in relation to the load placed on farm equipment as oysters grow. This will be particularly important during storm events when wave and current forces magnify loads on farm systems (Stevens et al., 2007). Managing the floatation and submergence depth is essential to ensure that oysters and their associated holding systems are not subjected to excessive wave energy transfer (Goseberg et al., 2017).

It is important to note that development of offshore oyster farm systems represent an opportunity to design more innovative farm systems that are more flexible, efficient, and work with the environment, and this could have positive implications for current nearshore farming (Heasman et al., 2020). Selection of suitable farm equipment is highly dependent on the level of exposure in the offshore environment; an existing subtidal technology may suit some nearshore exposed sites, but a complete revision will likely be needed to take on the open sea.

Subtidal and offshore systems that have been used experimentally in Europe and New Zealand, have considerable potential for adaptation for offshore in Tasmania and these are reviewed in the following sub-sections.

3.4.1.1. Longline systems

Longline systems comprise a single or double backbone line, held in the water column with floats along the backbone. The lines are held in place on the substrate by mooring lines, positioned at 45 degrees, and anchored to the substrate using concrete blocks or screw anchors (Figure 4). Culture equipment such as baskets or trays arranged in pack or ladder formations, or lantern cages are suspended throughout the backbone. Longlines are generally regarded as effective methods to support a large volume of production with minimal infrastructure (Stevens et al., 2008).

Positioning and layout of longline farm equipment affects farm productivity and equipment integrity. Subjecting lines to surface wave energy in high energy locations is likely to result in accelerated abrasion of rope and connective parts. As production moves to higher energy locations, longlines are better suited to be submerged 5-10 m below the surface. Submerged longlines are a good candidate for offshore conditions as their flexibility allows for movement in response to current and wave action, and submergence enables equipment to be situated out of direct influence of surface wave energy (Stevens et al., 2008).

Offshore oyster aquaculture can draw on experiences from high energy mussel cultivation experiments using submerged longlines (Buck et al., 2017; van den Burg et al., 2017; Mascorda Cabre et al., 2021). Balancing buoyancy has been highlighted as a significant challenge in offshore mussel longline systems. As environmental conditions deteriorate, maintaining the optimal buoyancy equilibrium becomes increasingly complex: the objective is to keep the lines adequately submerged to mitigate wave impact, all the while preventing excessive sinking (Kamermans et al., 2011). The design and amount of floatation buoys used also impacts wear and durability of the line; an example investigating high energy mussel cultivation in the German North Sea identified that the use of round buoys resulted in more stress on the lines and weakened connector point; this was mitigated by refitting the line with elongated buoys (Buck, 2007).

Consideration of local hydrodynamics is also important for setting the direction of longlines, to situate lines in alignment with the prevailing hydrodynamic energy. It is critical to ensure that longlines work with the hydrodynamic forces, rather than against them. Longlines have been demonstrated as a successful method to commercially cultivate oysters in high energy environments off California (Cheney et al., 2010), in addition to being used in offshore development projects in Chile, Italy and Belgium (Diaz & Sobenes, 2022, Roncarati et al.,2017. Longline systems are well established in Tasmanian subtidal leases, including the more exposed existing leases such as Great Oyster Bay, Bruny Island, and Norfolk Bay. However, the use of equipment such as floatation and anchors designed for lower energy sites is likely to be inadequate as the level of exposure increases. As an example, the German experimentation in the North Sea used 4 tonne concrete anchor blocks or wind turbine pylons in the case of co-location experiments (Goseberg et al., 2017). This could be an area that industry would focus on to develop into higher energy/offshore sites.

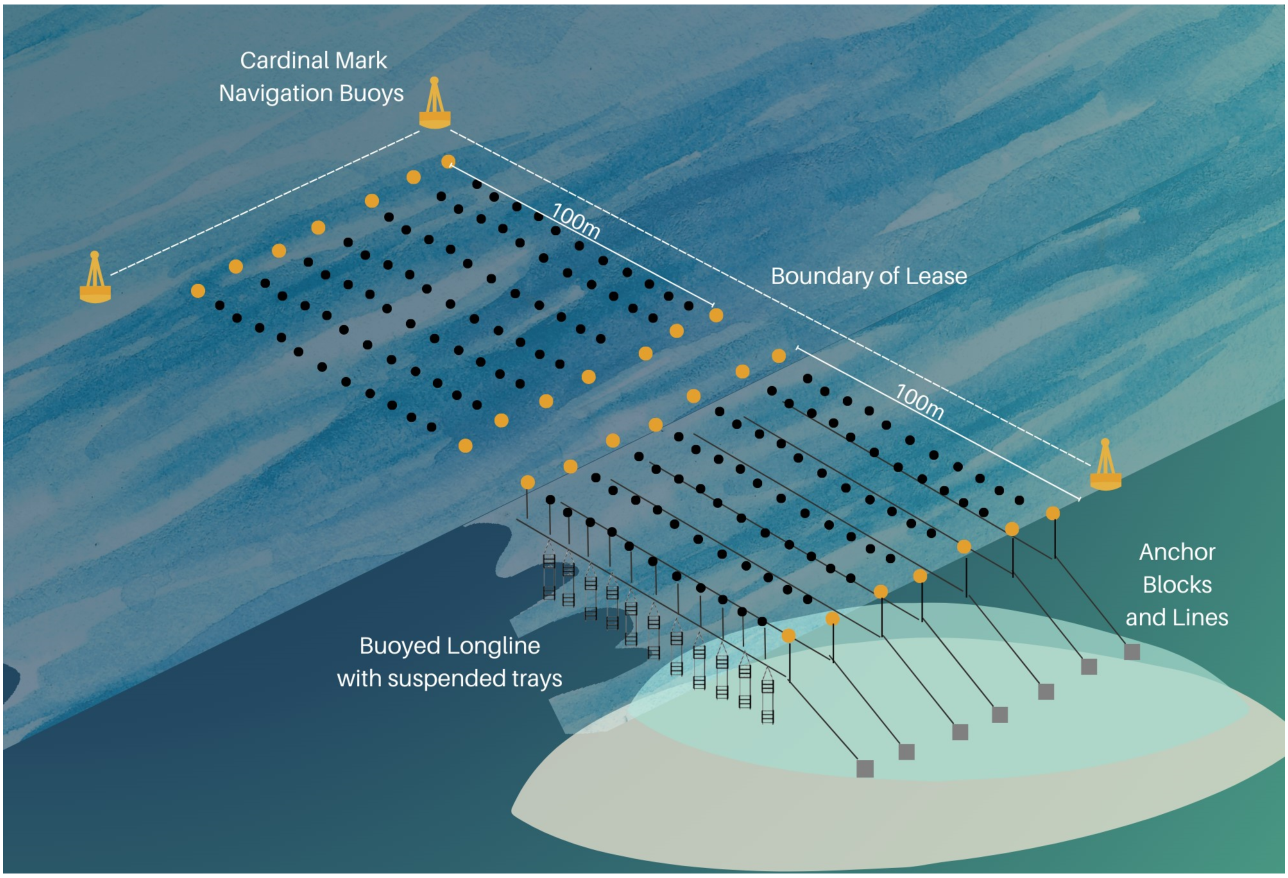


Figure 5. Schematic of longline farm layout – adapted from NSW Department of Primary Industries, 2018.

3.4.1.2. Bottom cage culture

Bottom cage culture has been used in offshore expansion projects in France (Barillé et al., 2020). Bottom cage frames weighed 600 kg, and within each cage there were 60 plastic mesh bags each containing 800 15.5 mm oysters. Offshore cages were placed on the substrate at 10 m, while intertidal cages were deployed at 2 m depth on high tide, with estimated 88% immersion time and grown out for 3 months. In this study, at the end of the experiment the offshore cages had 2.5x better growth and 1.5x greater shell length compared to caged located intertidally (Barillé et al., 2020). Improved growth observed in the offshore treatment was attributed to better water circulation, and reduced turbidity.

3.4.2. Production

During the production cycle oyster farmers carry out several processes to ensure farm efficiency and achieve optimal oyster quality. Farmers regularly bring oysters to shore to be graded, to kill fouling organisms by drying off equipment, adjust line positions and transfer oysters to different farm sites according to the production cycle. Oysters are harvested once they have reached marketable size and meat condition, usually after 18-24 months. Harvesting tends to be a manual process whereby baskets are transported to shore and manually emptied into bins before subsequent processing. Harvested oysters must be cleaned, graded, and sorted based on size and quality.

3.4.2.1. Grading

Grading increases in complexity the further that leases get from the processing facility, and more so if sites are subjected to rough seas that makes retrieval of lines and baskets unsafe. In one offshore mussel cultivation experiment conducted in the Gulf of Maine, investigators concluded that wind speeds of >35 km/h and wave heights of >2 m were prohibitive for maintenance activities and harvesting (Kamermans et al., 2007). For a greater reliance on sites further afield, adapting shore-based grading to on-water may need to be considered. Developing on-water grading systems could: a) decrease transportation time and associated costs, and b) maximise efficiency by grading when satisfactory weather windows are shorter. Better automation and reduced transportation time and costs for grading could help to justify grower investments into developing offshore sites. Greater efficiency in grading would have industry-wide benefit, with potential uptake not just restricted to subtidal or offshore sites.

3.4.2.2. Harvesting

Harvesting was identified as a key bottleneck following experimental oyster farming offshore from the Santa Barbara coast of California (Cheney et al., 2010). Adverse weather conditions and greater travel distances to offshore sites will pose a significant challenge for harvesting opportunities. Any absence from the market can lead to a loss of market position. Offshore oyster farms would benefit from increased harvest capacity (volume), automating harvest processes, and enhanced on-water efficiency (e.g., sorting oysters into size grades and bulk bins prior to landing). Improvements in harvest capability and efficiency developed for offshore would very likely have direct application to current farming operations.

3.4.3. Marine debris

Oyster aquaculture operations have the potential to generate marine debris using ropes, baskets, clips, and other culture equipment. Offshore sites are particularly susceptible to marine debris, due to the heightened likelihood of equipment loss during storm events. Marine debris can have detrimental effects on wildlife, lead to conflicts between local communities and farmers, and negatively impact overall ecosystem health. Relevant media reports associated with the New South Wales floods in 2021-22 provide examples of these concerns.

23/10/2022	*"It has been a bad year for the oyster farmers in Port Stephens. Not only have there been huge stock losses due to QX disease in Sydney rock oysters, but there have also been several wild weather events which have damaged some of the infrastructure on the leases. Some of the long lines have broken on at least four separate occasions, with loss of baskets. These baskets float away and usually end up in the mangroves at the northern end of the Cove."* *https://northarmcove.nsw.au/environment/oyster-debris-collected-and-removed*
17/08/2021	*"In the past few years, NSW oyster farmers have been put through the wringer on a regular basis. Drought, bushfire, flood and heavy rain have dealt blow after blow. In some cases, this has led to farmers losing not just all of their oysters, but their gear and infrastructure as well."* *https://eativitynews.com/nsw-oysters-enduring-in-adversity/*

3.4.4. Materials and plastics

The Pacific oyster industry uses a considerable volume of plastic equipment in the form of baskets, float cases, and clips. These components are made from different polymers, including low-density polyethylene (LDPE), high-density polyethylene (HDPE), or polypropylene (PP). Large volumes of old, unused plastic baskets on farm bases are an industry-wide issue that needs to be addressed. In a 2013 recycling feasibility study conducted by South Australian industry, it was estimated that over 4,000 tonnes of waste would be created by 2030 if valorisation opportunities were not found. Circular economy of plastics is a topic that remains on the Tasmanian oyster industry's research agenda particularly in the scope of the BE-CRC and any prospective increase in production. Development of offshore oyster farming will likely require some use of plastic, but strong consideration should be avoiding the use of plastics wherever possible.

Recycling aquaculture plastics presents a complex issue that currently lacks a readily available local solution. A feasibility study around recycling plastics completed by the South Australian Oyster Growers Association recommended that to be feasible, the industry needed to mutualise disposal requirements to obtain the best price for recycling (SAOGA, 2013). After this study, some actions of recycling were organised but the intrinsic difficulty to recycle the oyster farming equipment due to mixed construction materials and large amounts of biofouling continues to be a drawback to the development of efficient end-of- life solutions (FRDC, 2019; Summa et al., 2023). Mechanical recycling faces several challenges such as collection, effective sorting (HDPE and PP waste oyster baskets being disposed together), transportation (transport is costly unless baskets are baled or shredded first) and cleaning. Plastic must be contamination-free for recycling, which is rarely the case for plastic used in marine environments. Moreover, the recycling process usually degrades the raw material quality, called downcycling. This downcycling is more significant with the presence of impurities. That raises the question of managing the next generation of downcycled plastics. Chemical recycling, which depolymerizes used polymers to recover the monomer better avoids contamination, but it is more complex and expensive.

An alternative solution is the development of equipment based on biodegradable products, which would divert waste from landfill through industrial composting and reduce impact on the environment if it is inadvertently lost. Another strategy can be to rethink the raw material to make use of biobased materials and by-products from oyster farming itself, such as oyster shell powder (Figure 5). This can lead to two opportunities: (1) designing the most eco-friendly products (safe for the environment and enhances industry reputation), as well as; (2) a business opportunity through the valorisation of oyster industry waste (e.g., shells). For the success of such a solution, the products must meet the life span and physical quality of conventional plastics, for which there is not commercially viable at present.

Figure 6. Design of a circular economy for oyster farming equipment.

3.4.5. Logistical considerations for offshore operations

In selecting offshore sites, it is crucial to not only consider biophysical factors but also consider socio-economic considerations. As the distance between the shore and offshore farm sites increases, the costs associated with crew commuting from the shore base to the farm location also escalate. Traditional oyster farming practices use a series of repetitive tasks involving the transportation of oysters and baskets to and from the lease for onshore grading, sorting of stock, and the drying of baskets to eliminate fouling organisms before restocking. When considering the development of offshore sites, it becomes imperative for farmers to have access to a shore base or boat launching infrastructure within a feasible distance to ensure economically viable travel. Previous offshore oyster projects in Europe highlighted the increased distances from ports and major highways, and the economic impact that resulting logistical costs have on producers to be significant barriers to development (Brigolin et al., 2017; Galparsoro et al., 2020; Palmer et al., 2020; Barillé et al., 2020).

The availability of land bases in Tasmanian oyster producing regions has been identified by the industry as a significant obstacle to development. This challenge is further compounded by the need to contend with residential and recreational users for space. While the perspectives of competing users should be considered, they should not override other crucial factors in site selection, as this could lead to the allocation of unproductive waters. Additionally, the presence of essential infrastructure, including power, water, and transportation at land bases, is pivotal for ensuring the efficient operation of oyster farms.

3.5. Economic factors

The feasibility of offshore oyster farming depends upon return on investment, market demand, and production costs. The quality and consistency of the final product plays a critical role in shaping economic returns. Australia's demand for high-quality half shell oysters, evident from the substantial import of frozen products from New Zealand, underscores the need for offshore producers to maintain high quality standards.

While producers historically achieve this quality through a mix of intertidal culture type and processes, they will be required to refine their methods for offshore operations. Genetic selection for market traits has historically been employed to improve quality and should continue to apply in an offshore context.

Understanding the site's potential for finished product quality, volumes, and consistency will inform cost/benefit analyses to clarify the investment potential of offshore sites. This section will document the information required to populate a cost/benefit analysis for an offshore oyster farming and review cost/benefit of overseas experimentation examples. By building certainty around these economic factors, stakeholders can make informed decisions and optimise their offshore oyster production endeavours.

3.5.1. Marketability of offshore oysters

For offshore oyster farming, the cost-effectiveness of investments for Tasmanian grower's hinges on their ability to produce oysters that meet the stringent quality standards required to command premium prices in the half shell market. The primary market for Tasmanian-grown Pacific oysters revolves around the domestic half shell restaurant trade in major mainland cities (Schrobback et al., 2014). Even when volumes of Pacific oysters are exported, the final product typically caters to high-end restaurants in Asian countries.

Key traits of market importance were identified in a 2021-22 survey that included Tasmanian oyster growers, oyster grower-traders, and oyster traders (E. Chuku unpublished data). The top five preferred traits for each industry group, include meat condition, meat size, and meat-to-shell cavity condition index rating highest. Ensuring that oyster farms are in productive waters is central to achieving desired meat condition and size, as outlined in Section 3.2.6. Environmental productivity stands as a pivotal factor influencing meat condition, and it will serve as a determining factor for the advancement of site development However, the culture methods used in a productive site will refine the shell shape and meat-to-shell ratio that will enhance market appeal.

3.5.2. Optimising physical quality of the shell with meat condition

Offshore oyster farming research reporting has focused on growth parameters, such as shell length and meat yields (Pogoda et al., 2011, 2014; Barillé et al., 2020; Diaz & Sobenes, 2022). While the research concluded that offshore growth was generally improved, there is little, or an absence of data provided on shell quality indices such as hardness or shape. The experiments also lacked a clear comparison of qualitative characteristics such as meat to shell ratio, colour, smell, and taste compared to high-grade "inshore" products in the market. The visual presentation of the shell is important on the market and influences other preferred traits such as meat-to-shell ratio (Mizuta & Wikfors, 2019b). Oysters farmed in subtidal environments typically exhibit good meat condition due to continuous feeding facilitated by constant submergence (provided that environmental productivity is sufficient). However, this prolonged submergence can result in weak, chalky and brittle shells, as the rapid growth outpaces shell development (Mizuta & Wikfors, 2019b).

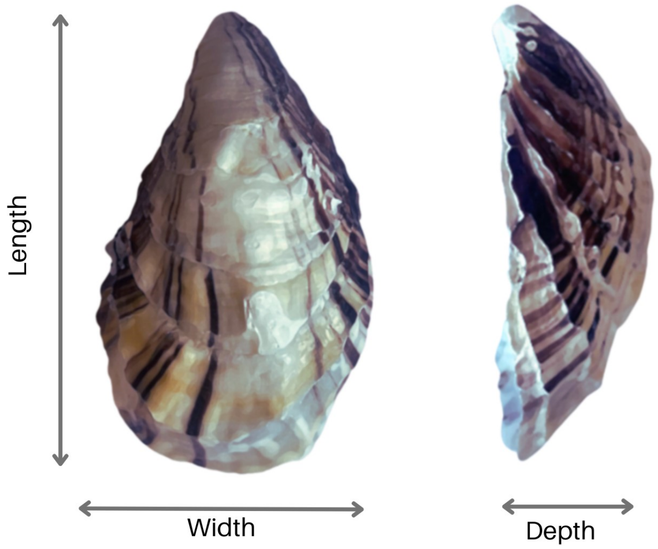


Figure 7. Preferred shell ratio 3L:2W:1D (adapted from Mizuta & Wikfors, 2019b).

Research into how offshore culture type can affect finished oyster quality is still in its infancy and warrants further investigation. Pogoda et al. (2011) cultured oysters at multiple experimental offshore locations in the German Bight and reported aesthetically pleasing shells and quality consistent with French half shell market products. The study involved submerging oysters in lantern cages at a depth of 4 m for seven months. A key outcome noted that oysters cultivated at the site experiencing stronger currents exhibited distinct shell morphology, with thicker shells and a more compact shape, and it was proposed that these adaptations may be in response to shell abrasion caused by the powerful currents rumbling oysters against the baskets. This suggests that there may be an optimal level of energy exposure necessary to ensure appropriate shell development and meat conditioning within a fully submerged cultivation system.

3.5.3. Selectively breeding for ‘offshore’ Pacific oysters

Selective breeding is commonly used in oyster farming to enhance profitability though producing oysters that are aligned with market demands (Gutierrez, 2018; Kube et al., 2018). The Australian Pacific oyster breeding program, operated by Australian Seafood Industries (ASI), has historically focused on selecting for traits of rapid growth, disease resistance, meat condition and shell shape (Kube et al., 2011). However, though ASI has focused on the above listed traits informed by the stakeholder priorities, some of the earlier breeding program work indicated that certain families gave superior performance in subtidal conditions (Thompson, 2006). Additional traits that would be beneficial for offshore farming include slower-growing shells and strong shell closing strength. Shell closing strength has been identified as a heritable trait and speculated to play a role in reducing summer mortality in countries where this is an issue such as South Korea (Ji et al., 2019).

3.5.4. Cost-benefit analysis

Previous offshore oyster farming research projects have provided little or no cost-benefit analysis. Effective cost-benefit considerations require an analysis of the following factors relevant to the development of high-energy oyster aquaculture sites:

a) Costs associated with increased travel;

b) Costs incurred or saved through equipment selection (e.g., robust/automated equipment with no requirement for rack construction);
c) Equipment lifespan, and risk of repair and replacement costs;
d) Costs incurred or saved through changes in production techniques
e) Costs incurred or saved through changes in production volume;

3.6. Collaborative opportunities

Synergies between offshore oyster farming and renewable energy sources have garnered increasing attention globally (Jansen et al., 2016; Buck et al., 2017; Holm et al., 2017; Buck et al., 2018). The co-location of oyster farms with existing renewable energy infrastructure, such as wind farms, offers the potential for mutual benefits and efficient utilisation of limited ocean space in countries such as Belgium and Germany where the coastlines are more constrained. Additionally, the integration of offshore oyster farming with integrated multitrophic aquaculture (IMTA) presents opportunities for collaboration and diversification within the aquaculture sector. The economic burden of increased distances has potential to derail development, especially in early stages. Co-location of developmental offshore oyster sites with other aquaculture or clean energy operations is a strategy that has been employed in European offshore projects.

In this section, shared-site, collaborative approaches that include offshore oyster faming in the North Sea are reviewed. Possible co-location within the Blue Economy and wider aquaculture sector is a potential strategy to control costs and expedite results in the initial offshore experimentation phase.

3.6.1. Co-location with offshore energy

Co-location of offshore oyster production with existing infrastructure, such as wind energy parks and aquaculture operations, has been explored in various studies. Examples from the North Sea region, including investigations in the Netherlands and Germany, highlight the potential benefits and challenges associated with co-location efforts (Pogoda et al., 2011; Pogoda et al., 2013; Jansen et al., 2016; Kamermans et al., 2018). In the German North Sea, oyster cultivation sites were established using infrastructure from existing wind parks and research areas in the German Bight. This research demonstrated the viability of co-locating oyster production with wind energy infrastructure, highlighting synergies for sharing transport and maintenance costs between these industries (Pogoda et al., 2011). Similarly, in the Dutch North Sea, native European oysters were at offshore sites within the well-established wind energy industry. This approach not only aimed to provide sustainable food production but also focused on habitat restoration. However, concerns surrounding risks, damages to infrastructure, and associated costs have presented challenges to the progression of co-location efforts (Jansen et al., 2016, Kamermans et al., 2018).

It is improbable that in the near-term that any development of Tasmanian offshore oyster farming will involve co-location with renewable energy technologies. Future synergies of the Tasmanian oyster industry with offshore clean energy have not yet been identified, this topic should be considered and evaluated as part of the broader assessment of site potential in Part 2.

3.6.2. Integrated multitrophic aquaculture

The prospect of offshore oyster farming as a component of integrated multitrophic aquaculture (IMTA) has gained considerable attention in Europe. In the Belgian North Sea, a research project co-located commercial European oyster production with reseeding of wild oyster beds, and passive fisheries (fisheries using techniques that do not disturb the seabed (Blauwe Cluster, 2019).

Furthermore, the integration of seaweed and other bivalve species within the framework of IMTA has garnered interest from the industry and should be explored as a potential avenue for future implementation

(Johnson et al., 2020). This approach holds relevance and viability in the short term, especially within the currently underdeveloped high-energy nearshore sites, including Great Oyster Bay, the D'Entrecasteaux Channel, and the Tasman Peninsula.

Integrated multitrophic aquaculture is typically undertaken with two distinct motivations. Firstly, the inclusion of extractive species serves to provide invaluable ecosystem services through the absorption of nitrogen compounds. Secondly, to integrate another commercially viable species to add economic value (Buck et al., 2018). Given the relatively low environmental impact associated with oyster cultivation itself, the rationale behind incorporating additional species must be compelling from a cost-benefit standpoint. To understand cost benefit assessment of co-location with other aquaculture species will be complex. Operators need to account for multiple species biological and physical requirements and limitations, as well as seasonality of growth and production planning. These endeavours will contribute to a comprehensive understanding of the potential synergies, challenges, and opportunities associated with these approaches (Smith et al., 2018; Johnson et al., 2020).

3.7. Knowledge gaps, challenges, and opportunities identified in the review

3.7.1. Knowledge gaps relating to biophysical factors

Detail and data on local environmental conditions experienced in Tasmanian offshore sites is lacking. Accumulating data on local hydrodynamics, water quality, and productivity would begin to contribute to understanding the production potential and equipment constraints of available offshore sites. Data on hydrodynamic forces is essential to inform equipment selection and design that would form an integral component of field testing in local exposed nearshore sites.

A significant knowledge gap lies in the understanding of local seasonal patterns and phytoplankton abundance. Likewise, the influence and importance of dissolved matter from river run-off as part of the total seston is not understood. This information is critical to feed into the productivity modelling and cost benefit scenarios that influence investment into Tasmanian offshore sites.

The review and consultation process have identified offshore biofouling management as a significant knowledge gap. These gaps encompass familiarity with the local organisms involved, which could facilitate the development of more targeted solutions. Within the literature, biofouling is frequently cited as a substantial impediment in international offshore developments. Collectively, this suggests that biofouling will emerge as a central focus for future research.

3.7.2. Site selection knowledge gaps

The utilisation of models holds the potential to enhance the optimisation of site selection within Tasmanian offshore areas being considered for oyster development. Nevertheless, it remains uncertain whether the models developed for inshore settings can be directly transferred to offshore sites. Should these models not directly translate to offshore settings, an opportunity arises to create dedicated offshore production models. There are also notable gaps in available in-situ data required to validate model assumptions. In-situ wave, wind, current, chlorophyll-a, temperature, and dissolved oxygen data are essential to evaluate investment potential of available high energy sites.

3.7.3. Key operational challenges for offshore oyster farming

The development of appropriate offshore oyster farming systems is a significant hurdle. Equipment and materials used for offshore farming needs to be tailored to withstand the challenges of the harsh biophysical environment, and it is likely that the requirement for greater durability and sophistication will influence the cost-benefit ratio. Lessons drawn from international projects, such as offshore mussel aquaculture, should guide equipment selection and design within the Blue Economy CRC. However, this should follow the establishment of a comprehensive understanding of the biophysical traits of Tasmanian offshore sites.

Another challenge will involve transitioning from highly manual inshore farming processes to operations with a higher degree of efficiency and automation. Harsh offshore conditions reduce the number of days that the farm may be accessed and worked. To address this, farmers must enhance their efficiencies, ensuring the necessary tasks are accomplished within a shorter timeframe. Implementing on-water grading systems has the potential to enhance overall efficiency by reducing costs and optimising weather-dependent work periods. Furthermore, adopting automation and refining harvesting methods can effectively address bottlenecks, thereby fostering industry-wide benefits. Linked to this issue is the challenge of shore base accessibility, which is crucial for operational efficiency but has been highlighted as a challenge due to competition from other users and limited infrastructure.

In consideration of expansion of the industry, the issue of increased and more efficient use of materials presents a challenge for oyster farmers and the wider aquaculture and fisheries sectors. Recycling feasibility for oyster farming plastics is hindered by sorting, transportation, and biofouling issues, in addition to limited capacity.

3.7.4. Economic knowledge gaps

There is a lack of specific data on return-on-investment figures and production cost estimates, including comparisons against equivalent inshore operations. These data are critical for a comprehensive understanding of the economic feasibility and return on investment of offshore oyster production.

The economic viability of offshore operations hinges on the oysters produced obtaining the favourable market prices achieved by existing operations. However, while the overseas research on experimental offshore oyster farming describes improved oyster growth in offshore trials, the literature does not provide a clear comparison between the quality attributes of the offshore oyster vs inshore oysters. Market traits of interest include meat-to-shell ratio, shape, appearance, hardness, and taste. At present there is little detail of traits that should be targeted in selective breeding for offshore oyster farming, but it is likely that meat condition, shell closing strength, and shell development will be favourable traits for offshore oysters. Furthermore, there is likely to be a need to develop novel techniques for phenotyping relevant traits. Additionally, research is necessary to understand how different offshore culture methods and their impact resulting oyster quality attributes.

3.7.5. Opportunities for collaboration

Although immediate prospects for co-locating offshore oyster production with renewable energy infrastructure may be limited in Tasmanian high-energy/offshore environments, IMTA and collaboration with other industries offers more diverse avenues for sustainable aquaculture development. Offshore IMTA involving oysters has been examined both as seafood production and as ecosystem restoration (Kamermans et al., 2018; Heasman et al., 2021; Navajan et al., 2023). Incorporating additional species diversifies the sources of income for oyster farmers. This reduces the financial risk associated with relying solely on oyster production and opens opportunities for other aquaculture (Knowler et al., 2020). Diversification of income can also provide a buffer against potential market access restrictions, which affect oyster farmers in the case of food safety restrictions and seasonal spawning events (Hossain et al., 2022).

Within the remaining life span of the Blue Economy CRC, it may be an attractive prospect to pool resources and accelerate progress by testing multiple species or multiple equipment developments at the same test sites.

4. Discussion

The Tasmanian Pacific oyster industry faces barriers to expansion stemming from coastal limitations, including depauperate waters in some areas of the state, competition for space, pollution, and technological inefficiencies. Expanding into offshore or higher energy nearshore environments may offer solutions to these challenges providing opportunities for sustainability and industry growth.

Internationally, various regions including Europe, New Zealand, and Latin America are exploring offshore oyster farming due to similar challenges faced by the Tasmanian industry. Economic potential, global demand for seafood, and climate change are driving factors. New Zealand has invested significantly in offshore shellfish research, supported by the Ministry of Business, Innovation and Employment and industry. Europe is also exploring offshore oyster aquaculture to meet demand for high-quality seafood and overcome challenges like declining water quality. Collaborative efforts and innovative models are being employed to scope out potential of energy production and aquaculture, as well as multi-species aquaculture.

Offshore oyster aquaculture in Tasmania holds strong potential but requires a comprehensive evaluation of various factors to determine its feasibility. Comprehensive assessment of the suitability of presently undeveloped nearshore high-energy sites, as well as exploring the potential for offshore farming locations, holds paramount importance. Here, the knowledge gaps lie in the absence of local data and applicability of existing models to offshore energy sites. It is essential that this knowledge is built as the next stage of oyster research in the Blue Economy CRC, as this will guide the development of appropriate infrastructure and technology to withstand high energy conditions.

The harsh conditions experienced at offshore sites necessitates the development of durable farming equipment. The design and layout of offshore farms needs to be carefully tailored to the biophysical characteristics of Tasmanian offshore sites such as prevailing current directions and speed, and wave height and depth. This is currently a key knowledge gap and may involve adapting existing systems such as subtidal longlines or designing novel farm systems. Opportunities for further collaboration with overseas researchers and engineers hold potential to accelerate development in this space.

Quality and consistency of oysters farmed offshore are key considerations for offshore feasibility. The literature had an absence of qualitative data regarding market and production traits of oysters produced in offshore studies. Characterisation and measurement of traits such as shell hardness, brittleness, meat to shell ratio, and shape is required to determine performance of oyster grown offshore, which will be critical to understanding the comparative success of offshore field trials and ultimately the feasibility of offshore oyster farming. Selective breeding is a well-established avenue to improving oyster performance and should be considered carefully in the planning of offshore experimentation.

Feasibility is inherently tied to cost benefit of operations. Comprehensive cost-benefit analysis for offshore ventures is currently limited and this will need to form a key component of future research. Understanding the economic implications of factors like production costs, travel expenses, and market stability is vital. Collaborative efforts among stakeholders can offer opportunity for shared costs and enhance offshore aquaculture's viability. Integrated Multi-Trophic Aquaculture, involving co-culturing of multiple species, offers an approach that may assist in accelerating progress for multiple aquaculture species in the remaining years of the Blue Economy CRC.

5. Conclusions and Recommendations

This scoping report has identified that the Tasmanian oyster industry is constrained in growth opportunities due to spatial limitations on water that is suitable for current farming practices. A high market demand for quality half shell oysters in the domestic market would likely underwrite a stepwise transition to higher energy nearshore sites, and potentially to true offshore farming. At this point there would likely be good opportunity to further expand into international markets. International research projects have provided very promising results for offshore oyster farming, and this gives further assurance that oyster farming expansion to higher energy environments is likely to be viable in Tasmania if approached in the right way. Many knowledge gaps and challenges were identified, and a comprehensive cost benefit analysis will be a fundamental component to provide further understanding of the investment potential. Hence, the key outcome from this report is the recommendation to progress to Part 2.

5.1. Future research needs

This scoping project has identified key knowledge gaps and challenges that are barriers to offshore oyster farming development in Tasmania. Within the remaining years of the Blue Economy CRC, undertaking a stepwise approach to the future research needs outlined in Table 3 should allow the Tasmanian oyster farming industry to farm existing available high energy areas, and consider viability of developments further offshore.

Part 2 should aim to address knowledge gaps around environmental data in Tasmanian sites, and how the biotic and abiotic variables translate to oyster production and productivity. This knowledge is required to inform field experimentation and equipment development in Part 3. Part 2 should also aim to define the assessment metrics for field experimentation that are critical to inform cost-benefit analysis and outline how success will be measured in offshore experiments.

Part 3 of the research will include the development and testing of improved farm systems and components, biofouling solutions, and on water capacity-building equipment improvements in both nearshore high energy sites and offshore. These developments will be underpinned cost-benefit analysis and comparison to inshore quality, efficiency, and cost.

Table 3. Framework of Part 2 research needs to address knowledge gaps and challenges identified in Scoping project; and outline of Part 3 research needs to move to equipment development and field-based experimentation.

Component	Research needs
Part 2	**Understanding site suitability and potential** • Characterisation of the status of existing shellfish leases allocated in high energy waters in Tasmania (number of leases/hectares available, barriers to development) (RP2, RP5). • Modelling of site suitability and productivity of existing nearshore high energy leases with available environmental data (RP2, RP4). • Hydrodynamic modelling to guide operational deployment in unlicensed leases (i.e., positioning lines) (RP1, RP4). • Biofouling assemblage study (results will drive Stage 3 projects for solutions) (RP4).

	Oyster performance and economics: criteria, techniques and approaches • Development of a standard to assess performance of oysters in field trials (RP2). • Definition shell and meat quality traits that are critical for market performance, including validation on existing inshore and deep-water product (baseline data) (RP2). • Development of rapid artificial intelligence data collection methods for growth, uniformity and shell shape, including validation of AI tool on existing inshore and deep-water product (RP2). • Identification of phenotypic traits of high importance to offshore oyster cultivation and incorporation into Australian Pacific oyster selective breeding program (RP2). • Cost benefit analysis modelling on existing nearshore high energy sites, based on site characteristics identified in Stage 2 site suitability work (RP2).
Part 3	**Equipment, engineering and field assessment** • Biofouling solution for high energy oyster farms, with potential for application on other structures (RP2, RP4, RP1). • Development of suitable floatation equipment for deepwater oyster longlines (RP1). • Field testing of experimental artificial intertidal oyster farm systems (RP1, RP2). • On-water grading equipment to drive efficiencies, reduce travel time/costs and improve finished product (RP1, RP2). • Basket/aquaculture plastic recyclability and potential for circular economy including waste baskets or shells (RP1, RP5).

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Appendix A – Project Synopsis

<table>
<tr><th>Project Leader</th><th>Project Team</th></tr>
<tr><td>Frances Huddlestone (Tasmanian Oyster Research Council)</td><td rowspan="7">Andrew Trotter (University of Tasmania)
Caleb Gardner (University of Tasmania)
Carmel McDougall (Griffith University)
Damien Guihen (University of Tasmania)
Duncan Spender (Tasmanian Oyster Research Council)
Gayan Gunaratne (BMT)
Ian Duthie (Tasmanian Oyster Research Council)
Kevin Heasman (Cawthron Institute)
Michael Heitzmann (University of Queensland)
Nagi Abdussamie (Blue Economy CRC)
Rowan Paton (Advance Composite Structures Australia)
Simon Albert (University of Queensland)</td></tr>
<tr><td>Report Author(s)</td></tr>
<tr><td>Frances Huddlestone (Tasmanian Oyster Research Council)
Rachel Breslin (University of Tasmania)
Andrew Trotter (University of Tasmania)
Vincent Mathel (University of Queensland)
Duncan Spender (Tasmanian Oyster Research Council)
Caleb Gardner (University of Tasmania)
Chris Carter (Blue Economy CRC)</td></tr>
<tr><td>Date Reported to the BE CRC</td></tr>
<tr><td>October / 2023</td></tr>
<tr><td>Approved by the BE CRC</td></tr>
<tr><td>Dr John Whittington, <i>BE CRC CEO</i></td></tr>
<tr><td>Project Objective(s)</td><td>BE CRC Milestones</td></tr>
<tr><td>• Define the need for offshore or higher energy water expansion within the Tasmanian Pacific oyster industry;
• Provide a brief review global approaches to offshore oyster aquaculture; and
• Assess the feasibility of offshore oyster aquaculture in Tasmania – identifying key considerations and challenges, knowledge gaps, and opportunities.</td><td>Progress reports:
PRO-0194
PRO-0205
PRO-0228
PRO-0253</td></tr>
<tr><td colspan="2">Utilisation/Commercialisation Opportunities</td></tr>
<tr><td colspan="2">N/A</td></tr>
<tr><td colspan="2">Intellectual Property</td></tr>
<tr><td colspan="2">None</td></tr>
<tr><td colspan="2">Confidentiality</td></tr>
</table>

Appendix B – Short Science Summary

A short science summary for this project is provided on the following page(s).

BLUE ECONOMY
COOPERATIVE RESEARCH CENTRE

Australian Government
Department of Industry, Science and Resources

AusIndustry
Cooperative Research Centres Program

2.21.001 – Scoping the need and feasibility for offshore Pacific oyster aquaculture in Tasmania SHORT SUMMARY

INTRODUCTION

Tasmanian oyster farmers contribute approximately one third of the total Australian oyster production of 9,000 tonnes. While globally, oyster aquaculture produced 6 million tonnes in 2020. The substantial domestic appetite for oysters is evident through the considerable quantities of imported oysters consumed in Australia, with over 8,000 tonnes of frozen oysters sourced from New Zealand annually. Considering the global oyster production levels and the consistent demand in the oyster market, the Tasmanian industry is presented with a significant opportunity for expansion.

The project involved reviewing examples of global research in offshore oyster farming, describing initiatives from several countries that have invested significantly in offshore oyster research activities. Overseas, coastal areas that face spatial limitations and pollution have led oyster producers to explore offshore farming. Other countries have explored offshore expansion driven by the increasing demand for high quality domestically produced seafood, and the economic potential in meeting this demand.

The Tasmania's oyster industry was involved in the scoping process. The project team held theme meetings that interested farmers were encouraged to join. Divided into biophysical, operational, and economic considerations, these meetings involved the team of experts and industry participants. Attendees were briefed on the literature review findings and encouraged to provide feedback and commentary.

KEY POINTS

In the examples of overseas research cited, key themes emerged relating to identifying and assessing site suitability, and the importance of efficient farm systems and processes. Favourable growth performance was reported offshore, as were challenging conditions, with an emphasis on biofouling as a key constraint.

Key knowledge gaps identified through the project include:

- Limited data on local environmental conditions hindering a developed understanding of offshore site potential.
- Uncertainty about the applicability of inshore site selection models to offshore settings.
- Limited information of the specific traits that should be targeted in selective breeding for offshore oyster farming.
- An absence of return-on-investment data and clear comparisons of quality attributes between offshore and inshore oysters, impacting the economic viability and pricing of offshore oyster production.
- An absence of specialised, durable equipment, more efficient and automated processes.

Figure 1. Project Team site visit at Dart Island hosted by Steve Leslie and Yvonne Young. *Figure courtesy of Oysters Tasmania*

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THE CHALLENGE

The offshore oyster aquaculture scoping project faced several key challenges. A significant one was the limited availability of literature on this relatively new and globally emerging field, with a notable absence of data on cost-benefit analysis. Additionally, the team grappled with ensuring that the project's outcomes remained pertinent to the existing industry. Securing and maintaining the industry's engagement and endorsement is imperative for oyster research within the Blue Economy CRC to be considered successful. Furthermore, we were challenged to deliver a research plan that was not only relevant but also feasible, capable of positively influencing the expansion of offshore/high-energy oyster aquaculture within the specific time frame of the Blue Economy CRC.

THE OPPORTUNITY

Production expansion opportunities were identified in the number of unlicensed oyster leases located in deeper, higher energy waters around the Tasmania. Feedback from industry indicated that there were several barriers in developing the vacant leases, including equipment suitability, logistical concerns, and a lack of confidence around the primary productivity of the sites to justify investment. The project highlighted that research, development, and extension through the Blue Economy CRC would contribute toward addressing these barriers.

OUR RESEARCH

PROJECT AIMS

The aims for this scoping project were:

- Define the need for offshore or higher energy water expansion within the Tasmanian Pacific oyster industry;
- Provide a brief review of global approaches to offshore oyster aquaculture; and
- Assess the feasibility of offshore aquaculture in Tasmania – identifying key considerations and challenges, knowledge gaps, and opportunities.

LITERATURE REVIEW AND DISCUSSION THEMES

- Review of global approaches to offshore oyster farming.
- Biophysical feasibility of offshore oyster production (e.g., Hydrodynamics, water quality, environmental productivity, biofouling).
- Methodology and considerations for site selection (Data availability and limitations, application of established models).
- Selective breeding for offshore oyster traits.
- Operational factors (Farming equipment, production processes, materials, logistical considerations)
- Economic factors (marketability and product quality, cost/benefit analysis)
- Collaborative opportunities

Figure 2. Oyster farm at Dart Island, Tasman Peninsula.
Figure courtesy of Oysters Tasmania

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BLUE ECONOMY
COOPERATIVE RESEARCH CENTRE

Australian Government
Department of Industry, Science and Resources

AusIndustry
Cooperative Research Centres Program

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OUTCOMES

International research projects have provided very promising results for offshore oyster farming, and this gives further assurance that oyster farming expansion to higher energy environments is likely to be viable in Tasmania if approached in the right way. A high market demand for quality half shell oysters in the domestic market would likely underwrite a stepwise transition to higher energy nearshore sites, and potentially to farming further offshore.

NEXT STEPS

This scoping project has identified key knowledge gaps and challenges that are barriers to offshore oyster farming development in Tasmania. Within the remaining years of the Blue Economy CRC, pursuing the future research needs outlined should allow the Tasmanian oyster industry to farm existing available high energy areas, and consider the viability of developments further offshore.

This scoping project concluded to outlining a recommended three-part research, development, and extension approach for the Tasmanian oyster industry within the 10-year duration of the Blue Economy CRC.

Part 1: **Scoping Project**

Part 2: **Understanding site suitability and potential**

Oyster performance and economics: criteria, techniques, and approaches.

Part 3: **Equipment, engineering, and field assessment**

PROJECT TEAM

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PROJECT REPORTS/PUBLICATIONS

Huddlestone, F. et al (2023). Scoping the need and feasibility for offshore Pacific oyster aquaculture in Tasmania, 2.21.001 – Final Project Report. Blue Economy Cooperative Research Centre.

SHORT SUMMARY AUTHOR

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OUR VISION

To enhance the development of Australia's sustainable blue economy through the delivery of world-class, industry focussed research into integrated seafood and renewable energy production systems.

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