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A CASE STUDY FOR REGENERATIVE AND RESTORATIVE AQUACULTURE

# Marine Pearl Farming

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Fishing and farming of pearls from oysters and the use of pearl oyster shell has occurred throughout human history (Zhu, Southgate and Li, 2019). In recent decades, it has provided a high value product for market; in 2021, global production of pearl oysters in marine environments directly attributed to aquaculture totalled 1,415 tonnes, 0.0045% of the total global aquaculture production from marine areas (marine environments excluding brackish waters), for a production value of nearly $200 million, 0.22% of the total global aquaculture value. However, the variability in reporting pearl production which draws on both wild caught and hatchery bred stock as well as potential underreporting mean production and associated value may be 1-3 x higher than these estimates. In several nations, the higher relative value of pearl oysters makes this sector an important source of economic opportunity, with flow-on benefits and security for social needs. For example, in French Polynesia, pearl farming is the second largest economy, behind tourism, spanning approximately 30 islands and an estimated 9,000 hectares. In the Philippines, pearl farming is one of the country's most significant fishery sectors, with revenue increasing from $9 million U.S. dollars (USD) in 1991 to $15 million USD in 2015 (Bondad-Reantaso *et al.*, 2007).

However, total production volumes and the value of marine pearls can be highly variable. In Australia, the value of pearl production decreased nearly 40%, from $190 million USD in 2000 to $71 million USD today (ABARES, 2022), largely due to increased supply of lower-value product from pearl aquaculture in freshwater environments in Asia. In the Philippines, stock losses and shell deformities have increased substantially, and disease issues have become significant enough to make some formerly productive areas unworkable (FAO, 2023). More recently, the direct impact of the COVID-19 pandemic on farming logistics contributed to a drop in production volumes globally, resulting in demand exceeding supply for the first time in 20 years and a marked increase in the price of marine pearls over the last 12 months.

In 2021, global production of pearl oysters through aquaculture in marine environments were reported for nine countries in the Food and Agriculture Organization of the United Nations (FAO) Fisheries and Aquaculture Statistics (Table 1). An additional six countries farm and/or harvest pearl oysters but do not display production statistics: the Philippines, Vietnam, Myanmar, Fiji, the Cook Islands, and the Gulf region, including Bahrain (natural pearls only) and the United Arab Emirates (UAE)[1]. Across all countries, the primary species cultured are South Sea Pearls (*Pinctada maxima*), Tahitian Black Pearls (*P. margaritifera* (var. *cummingi* and var. *typica*), and the Akoya Pearls (P. *fucata, P. martensii, P. radiata*, and *P. imbricata*), along with cultivation of *Pteria spp.*, including *Pteria penguin* and *Pteria sterna,* for mabe pearls. In addition to the pearl itself, the shell of *Pinctada* spp. oysters is used for nacre and its oyster meat can be consumed. Hatchery-produced oysters are predominantly used for pearl farming, with Australia being the primary geography in which oysters are harvested from the wild for further culturing in aquaculture sites.

Table 1. **Marine pearl oyster production volumes reported in FAO Fisheries and Aquaculture Statistics, 2021 (FAO, 2023).**

| Country | Production Region | Primary ASFIS[2] | Live Weight (Tonnes) 2021 |
|---|---|---|---|
| **French Polynesia** | Pacific, Eastern Central | Blacklip pearl oyster | 1365 |
| **Indonesia** | Pacific, Western Central | Pearl oyster shells nei* | 1000ˆ |
| **Australia** | Indian Ocean, Eastern | Pearl oyster shells nei | 200 |
| **Indonesia** | Pacific, Western Central | Penguin wing oyster | 18.6 |
| **French Polynesia** | Pacific, Eastern Central | Pearl oyster shells nei | 17.14 |
| **Japan** | Pacific, Northwest | Pearl oyster shells nei | 12.6 |
| **Indonesia** | Indian Ocean, Eastern | Pearl oyster shells nei | 10 |
| **China** | Pacific, Northwest | Pearl oyster shells nei | 2.01 |
| **Papua New Guinea** | Pacific, Western Central | Pearl oyster shells nei | .47 |

[1] Production statistics from these countries are either unreported due to low volume or reported in groupings that cannot be disaggregated from other species, e.g., 'marine molluscs nei', 'marine shells nei'.

[2] Aquatic Sciences and Fisheries Information System; list of species for fishery statistics purposes published by the Food and Agriculture Organization.

* nei, refers to the species and products not elsewhere included in FAO statistics.

ˆ Figures from global capture production database due to species and quantity being reported as wild caught oysters.

## ENVIRONMENTAL CONTEXT

Like other oyster species farmed in marine environments, pearl oysters are grown without the use of feed, relying on food naturally available in the surrounding waters for growth. Yet unlike oysters farmed for food, pearl species are grown with some differences. The shortest timeframe for culture is two years, but the longest timeframe is eight years. This length of time is required for production of the pearl and can enable successive seedings and multiple pearls to be produced. Juveniles and mature pearl oysters can also be grown on or collected from the seafloor (wild harvest), though most production occurs from hatchery-bred oysters that are then transferred to baskets or nets with individual pockets and hung on floating long lines or rafts for further cultivation or attached directly to hanging lines (Figure 1). Because pearl oysters are held or attached as individuals, they are typically farmed at a lower density than other oyster species. (For example, in Australia, pearl oysters are farmed on longlines approximately 200 metres in length with pocketed baskets spaced 50 metres apart [Jelbart, Schreider and MacFarlane, 2011]). This approach is required to support effective growth and maintenance of the pearl oysters, but it also increases the certainty of there being few, if any, negative impacts from this form of bivalve farming on benthic environments, such as changes in sediment characteristics or associated faunal communities from waste or shading (Jelbart, Schreider and MacFarlane, 2011).

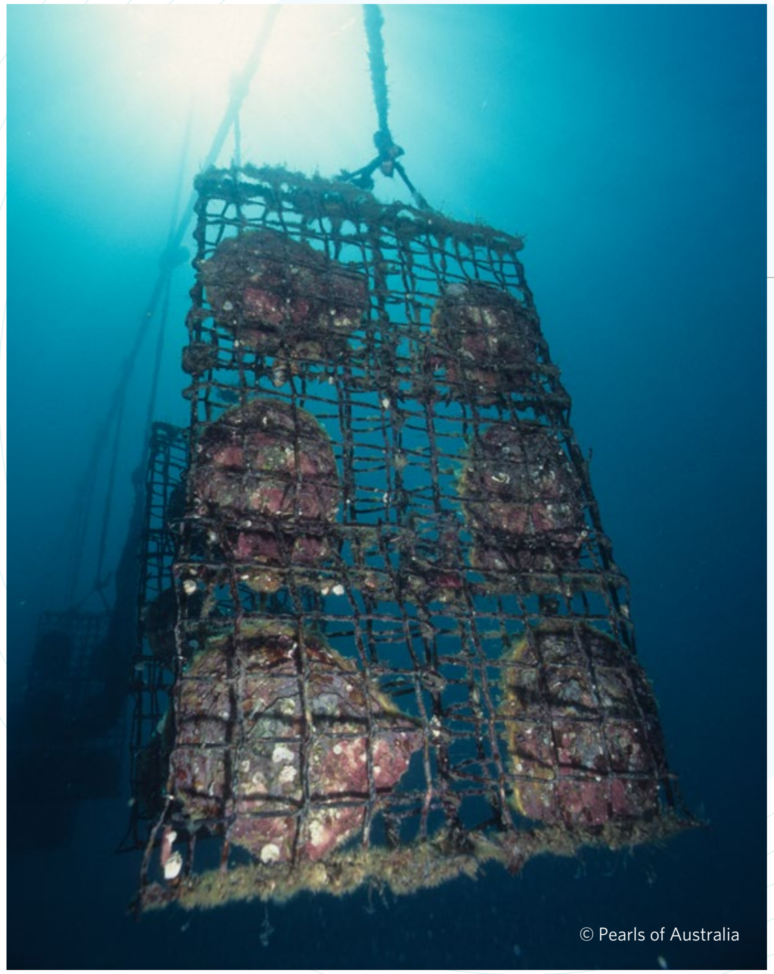

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Figure 1. ***Pinctada maxima*** **hung in oyster baskets from longlines at Cygnet Bay on the northwest coast of Australia.**

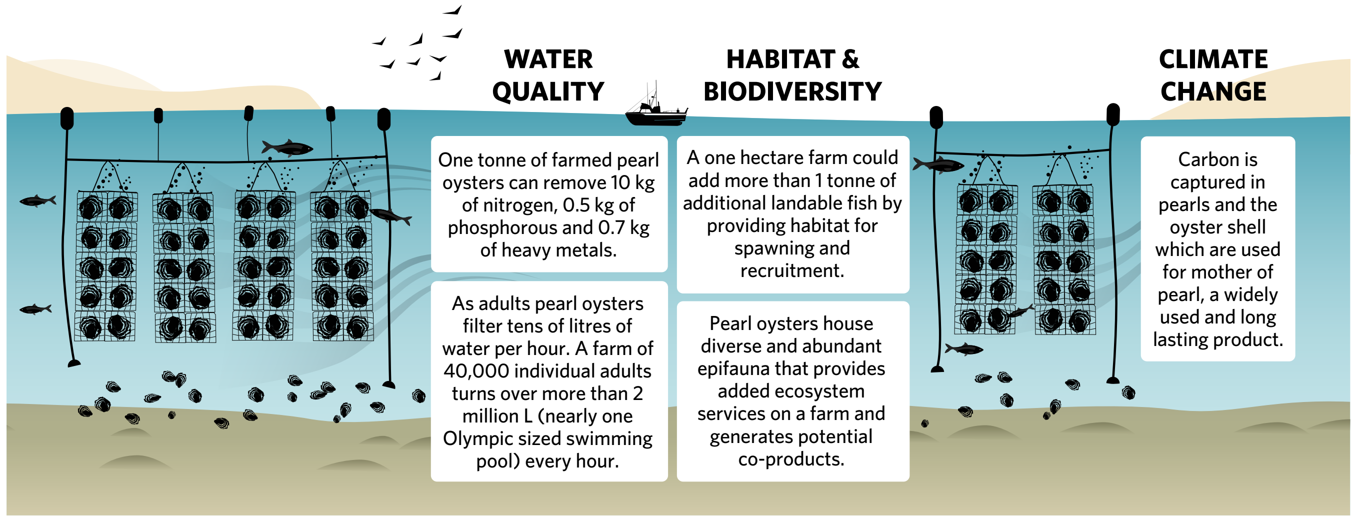
Pearl oysters are primarily farmed in tropical and subtropical environments, the highest latitude environments for farming being New South Wales on the east coast of Australia (32°S) and several southern prefectures in Japan (32-34°N). In these environments, rapid growth of epibionts (settling plants and animals) can occur. This epibiota, typically referred to as biofouling, must be managed for the risk it presents to the farming stock and its productivity – including increased stress, decreased growth rates, and increased susceptibility to disease – and the broader environment – including the facilitation of the introduction and spread of non-native species (Bishop *et al.*, 2017). Regular cleaning of the oysters and baskets, nets, and holding longlines is required, usually every 4 to 16 weeks, while considering the additional need for operational resources and the stress of overhandling on the stock and ecosystem (Colman, 2020). Biofouling animals, such as boring organisms, can also lead to physical damage to stock and add substantial weight to infrastructure, introducing the risk of stock detaching from longlines. Biofouling management is a direct cost to farmers, estimated in the aquaculture industry as a whole to be 5-10% of production costs; the more frequent maintenance regimen for pearl oysters means costs in this sector are likely even higher (Lane and Willemsen, 2004; Bannister *et al.*, 2019).

## ENVIRONMENTAL BENEFITS

The ecosystem services associated with farming pearl oysters are like those for edible oysters, but there are some specific characteristics of these systems that may make the provision of some services more or less prominent (Figure 2). As one would expect, the longer an oyster is in the water, the more it is able to filter. Pearl oysters have also been reported to have some of the highest rates of water filtration of all bivalves; according to Lucas (2008), a single adult pearl oyster can filter up to 22 litres per hour, while Yukihira, Klumpp and Lucas (1998) recorded 50 to 100 litres per hour in *Pinctada margaritifera* and *P. maxima* oysters measuring 150 or more millimetres in shell height. Laboratory studies have identified clearance rates of 2 to 4 litres per hour per oyster at smaller (juvenile) sizes and optimum temperatures (Mondal, 2006; Ye *et al.*, 2022). However, the lower biomass typically carried on the farm means the benefit of water filtration, per tonne of oysters or hectare of farm, as a net value may be less, depending on stocking densities, the size of the oysters on the farm, and local environmental conditions. Several studies have identified that amongst environmental variables, temperature influences filtration rates while other factors, such as salinity, often do not, leading Zu Ermgassen *et al.* (2013) to propose a standard formula for estimating filtration rates that accounts for this influence:

$$FR = 8.02W^{0.58}e^{-0.015(T-27)^2}$$

where $W$ is oyster dry tissue mass in grams and $T$ is temperature in degrees Celsius. Developing models such as this, that can be used across species, geographies and environmental conditions, is important in arriving at a more consistent understanding of the potential environmental benefits of bivalve aquaculture.



One tonne of farmed pearl oysters can remove 10 kg of nitrogen, 0.5 kg of phosphorous and 0.7 kg of heavy metals.

As adults pearl oysters filter tens of litres of water per hour. A farm of 40,000 individual adults turns over more than 2 million L (nearly one Olympic sized swimming pool) every hour.

A one hectare farm could add more than 1 tonne of additional landable fish by providing habitat for spawning and recruitment.

Pearl oysters house diverse and abundant epifauna that provides added ecosystem services on a farm and generates potential co-products.

Carbon is captured in pearls and the oyster shell which are used for mother of pearl, a widely used and long lasting product.

Figure 2. **Potential environmental benefits of regenerative and restorative practices in marine pearl farming.**

Pearl oysters could also play a role in bioremediation, extracting large quantities of organic nutrients and heavy metals. (This service would be relevant where the meat of the oyster isn't used or where depuration can occur to mitigate the human health risk.) Gifford *et al.* (2005) estimated that each tonne of *P. imbricata* harvested in Port Stephens in New South Wales, Australia, resulted in approximately 703 grams of metals, 7.452 kilograms of nitrogen, and 545 grams of phosphorus being removed from surrounding waters. The magnitude of these benefits is important to accurately and consistently quantify.

> **It is likely pearl farming provides a range of valuable ecosystem services, making it a unique proposition in comparison to other gemstones (e.g., diamonds).**

Production of mother of pearl from the shell of pearl oysters also raises the question of whether the carbon contained in the shell could also be intentionally used as a long-term carbon sink. Oyster shells are composed mostly of calcium carbonate ($CaCO_3$), converting atmospheric carbon dioxide ($CO_2$) and retaining a high carbon content. A report on the opportunity for carbon certification and neutrality in the Australian oyster aquaculture industry identified the standard estimate of 12% of oyster shell mass (12 grams per 100 grams of shell) to be carbon; for two commercially important food species, the Sydney rock oyster (*Saccostrea glomerata*) and Pacific oyster (*Crassostrea gigas*), this quantity would create a carbon sink of approximately 32.5 grams and 83.8 grams of carbon per oyster shell, respectively, at market (Marshall, 2022). However, the formation of bivalve shell in open systems is likely a net source of CO2, because under most growth conditions, bivalves release marginally more $CO_2$ through respiration and the calcification process than they ultimately store (Han, *et al.*, 2017).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Farmed pearl oysters can be cultivated in similar ways to edible oysters and can offer similar environmental benefits, including water filtration and habitat creation.

There is an emerging opportunity to account for the exchange and quantity of $CO_2$ generated and sequestered across the life cycle of production more effectively. This can be supported by life cycle assessment (LCA) that measures the impacts of resource inputs at all stages, including positive impacts such carbon sequestration in shell, as well as nutrient bioextraction (Ray *et al.*, 2018), see Box 1.


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## Box 1. Cygnet Bay Pearl Farm – Western Australia, Australia

Cygnet Bay Pearl Farm (CBPF) on the northwest coast of Western Australia is one of two farms operated by Pearls of Australia (PoA), a company farming Western Australian Silverlip Pearl Oyster (*Pinctada maxima*) using both wild capture and hatchery operations for sourcing seedstock. CBPF operates in a relatively sheltered inshore marine lease, adjacent to a land-based hatchery, and has an open ocean lease associated with wild oyster fishing, seeding and grow-out. These areas are used to produce beaded cultured pearls, known in the trade as South Sea pearls, and non-beaded cultured pearls, known as keshis or seedless pearls.

In 2023, an assessment of the environmental, social, and corporate governance (ESG) and life cycle analysis of the company's operations was undertaken. The assessment showed that CBPF meets or exceeds essential requirements in all aspects of ESG considered critical to highly sustainable aquaculture (O'Shea *et al.*, 2019), including the capacity, ethics and management measures of the farmer. CBPF adheres to the Pearling Environmental Code of Conduct and has Marine Stewardship Council certification, meeting independent, third-party ecological sustainability standards. The life cycle analysis identified that the amount of nitrogen removed via bioextraction was markedly greater than inputs to the environment from operations, resulting in a positive net effect for marine eutrophication.

PoA also provides critical support for research and development, founding and hosting the Kimberley Marine Research Station (KMRS) and supporting a variety of projects run by university and government research institutions. Since 2017, KMRS has collected environmental data on the Cygnet Bay area, including information on variables that could enable estimates of site-specific water filtration rates, such as regular sampling of water temperature. Because CBPF records detailed operational and environmental information, site-specific estimates of several ecosystem services can be made. For example, general clearance rates have been previously reported for *P. maxima* of 2.8 litres per hour for small oysters (37 millimetres shell height), 11.5 litres per hour for medium oysters (83 millimetres), and 47.1 litres per hour for large oysters (185 millimetres), with clearance rates being closely correlated with body size (Yukihira, Klumpp and Lucas, 1998). By binning data on the size of individual oysters held on site at Cygnet Bay into categories spanning these sizes and aligning this biomass with corresponding clearance rate estimates, it is estimated that 2.3 million litres of water is being filtered every hour. It would be possible to combine these data with the temperature records to generate more accurate time series of water filtration (zu Ermgassen *et al.*, 2013).

PEARLS OF AUSTRALIA
CYGNET BAY · BROKEN BAY

The Sustainable Value Generator

While the epibiota associated with pearl oyster stock and infrastructure presents a challenge to farming, biofouling communities can also provide habitat for other fauna. Bivalve aquaculture can enhance the abundance and richness of fauna, including fish species that have commercial or recreational fishing value. Barrett *et al.*, (2022) quantified a median effect from published studies of oyster aquaculture (including pearl oysters) of 1.7 times the abundance and 1.3 times the diversity of fish of comparable natural habitats without aquaculture farms. Species commonly found colonizing aquaculture farms include bivalves, sponges, tunicates, and macroalgae, and collectively, this epibiota can provide ecosystem services in its own right, such as further increasing water filtration and creating food for other species (Corrigan *et al.*, 2022; Underwood, van der Reis and Jeffs, 2023). Recent research on mussel farming has identified that fish foraging within mussel farm habitats have higher concentrations of lipids in their diet, meaning those fish had better nutrition and were in better nutritional condition than fish foraging at nearby non-aquaculture sites (Underwood, van der Reis and Jeffs, 2023). There is a need to identify novel opportunities to manage biofouling that can reduce its environmental and economic impacts while capitalizing on the ecosystem services that may be provided, such as by identifying a commercial use for the epibiota and new revenue streams or by co-culturing seaweed with pearl oysters, which may provide a protective measure for the oysters from biofouling (Morris, 2018).

Pearl oysters continue to provide opportunities beyond ornamental and craft. The extended production cycle and relative complexity of pearling and pearl farming make it a labour-intensive activity with high rates of direct employment. Additionally, because the growth of pearls and their quality can also be sensitive to environmental variations, pearl farms are often located in remote areas. The transport and communication infrastructure that is developed to support the industry can also benefit local communities. Pearl farmers also often turn to eco-tourism to diversify revenue, maximising the use of existing infrastructure and, importantly, engaging consumers by sharing the story behind the pearls. On remote islands in French Polynesia, pearl farming has been an effective way to support alternative livelihoods as coconut cultivation and the production of copra (dried coconut flesh for extracting oil) has declined. Most marine farmers in the Philippines and Indonesia engage with the community on education, mangrove conservation and replanting, beach cleaning, and reef restoration or other projects.


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A grower dives to harvest pearl oysters from the ocean floor.

## POTENTIAL BENEFITS OF PEARL FARMING

### Habitat and biodiversity

Epibiota commonly occurring on pearl farms can be abundant and diverse. This biofouling could be an important source of habitat or food for fauna in the environment, or an additional source of commercial product.

### Water quality

Like all oyster species, pearl oysters filter water, with species-specific filtration rates often reported to be higher in *Pinctada* species than other oysters. Water filtration can contribute to remediating eutrophication through the uptake of nutrients (nitrogen, phosphorus, and carbon) and heavy metals in the pearl and shell.

### Climate change

Carbon cycling and uptake/absorption occurs within oyster shells, which could be directed toward long term storage or sinks, including product-based sinks such as biomaterials.

### Sustainable food, resources, and livelihood

Pearl production is an important economic opportunity associated with the provision of raw materials through ornamental resources, and the oyster can be used for food. Pearl oysters, therefore, provide the opportunity to produce a comparatively higher value product or products with 100% utilization.

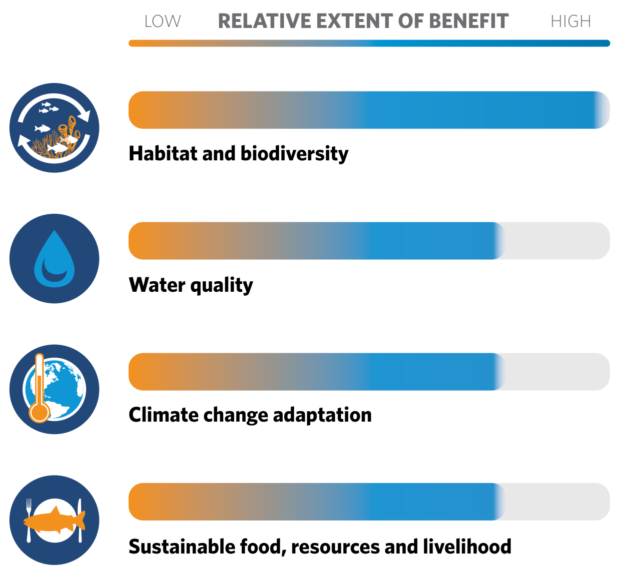
If farmed well, pearls represent a product differentiated by their sustainability in the gemstone market. The nature of pearl farming and low stocking densities can result in these aquaculture systems being relatively benign (e.g., little or no impacts on benthos) or, in some cases, the benefits provided offer the potential for a net-positive environmental outcome.

The value of pearls and labor-intensity of farming (e.g., seeding of the pearl) can contribute to economic and social security, particularly in remote areas.

The cultural importance and long history of pearling provides opportunities for tourism, education, and cultural or spiritual experiences.

Figure 3. **Potential extent of environmental benefits from marine pearl farming.**

Extent of benefits is indicative only and relative to each other and similar systems.



## IMPLICATIONS FOR MONITORING AND EVALUATION FOR RESTORATIVE AQUACULTURE

Like all oysters, the growth, and survival or pearl oysters are intrinsically linked to the health of the marine environment. Temperature, salinity, acidity, and nutrient flow all influence the formation of nacre, which determines the shape, size, colour, lustre, and surface characteristics that are appreciated and valued in pearls. The formation of nacre can happen naturally or be triggered by humans, in which case, the skills, care, and sometimes inspiration of pearl farmers also greatly influence the quality of each gem harvested.

### Habitat and biodiversity

More information is needed on the potential biodiversity and commercial benefits of epibiota associated with pearl farms, both at individual farms and across operating systems and different locations.

Monitoring and evaluation of biofouling will need to account for trade-offs in risks (i.e., biofouling risks, reduced productivity) and benefits.

### Water quality

Farming of oysters to produce pearls raises important questions about how environmental benefits can be consistently monitored and valued across the oyster aquaculture sector, and the bivalve and mollusc sectors more broadly. Consistent approaches to valuing common services such as water filtration rates, bioextraction, and denitrification need to be developed and used to standardise measurements.

Better understanding is needed on whether epibiota also contribute positively to ecosystem services in the local environment by, for example, adding to the capacity for water filtration, providing food for fish to forage, or by increasing biogeochemical cycling to increase nitrogen and carbon reduction.

### Sustainable food, resources, and livelihood

Life cycle assessment and regular collection of data on life cycle activities and inputs – in particular fuel and energy use – will support a more accurate understanding of the sustainability value of pearls in comparison to other gems and marine aquaculture products (e.g., their comparative greenhouse gas emissions), given that other environmental impacts, such as the effects on marine eutrophication, is likely to be uniquely beneficial. It will also support a more accurate understanding of how the uptake of dissolved carbon might reduce emissions from the broader production system, including hatchery production upstream and product processing downstream.

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