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SPECIALTY SECTION

This article was submitted to
Marine Fisheries, Aquaculture and Living
Resources,
a section of the journal
Frontiers in Marine Science

RECEIVED 26 January 2023

ACCEPTED 13 March 2023

PUBLISHED 24 March 2023

CITATION

Loayza-Aguilar RE, Huamancondor-Paz YP,
Saldaña-Rojas GB and Olivos-Ramirez GE
(2023) Integrated Multi-Trophic
Aquaculture (IMTA): Strategic model
for sustainable mariculture in
Samanco Bay, Peru.
Front. Mar. Sci. 10:1151810.
doi: 10.3389/fmars.2023.1151810

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Integrated Multi-Trophic Aquaculture (IMTA): Strategic model for sustainable mariculture in Samanco Bay, Peru

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The development of industrial mariculture in Peruvian coasts will continue to grow according to global trends; however, it is characterized by being mostly monospecific, resulting in ecosystemic impacts due to organic matter, which deteriorate the benthic system and encourage eutrophication, negatively affecting biodiversity and fishery resources, which in a long term could turn the activity into an unsustainable practice. Therefore, it is imperative to adopt new production models, focused on the sustainability principle, such as Integrated Multi-Trophic Aquaculture (IMTA), that allow for greater efficiency, competitiveness, and profitability, while guaranteeing environmental balance. In this context, the present study has addressed the problem of *Argopecten purpuratus* cultivation in Samanco Bay, in which, based on a diagnosis of the bay's conditions, details of the cultivation, and a thorough analysis of the IMTA concept, a strategic model for mariculture is proposed in order to be adopted by private companies, after a validation process. These concepts can be transferred for their adaptation to other scenarios. Furthermore, it is expected that the academic sector, private companies, and the competent authority will be able to intervene synergistically in this process.

KEYWORDS

integrated multi-trophic aquaculture, mariculture, Samanco bay, organic matter, extractive aquaculture, macroalgae

1 Introduction

Aquaculture is an activity that has provided food for humanity since the ancient ages (Beveridge and Little, 2002). Its origins date back to 3500 B.C. from ancient China (Vela and Ojeda, 2007). However, as a productive-economic activity, it has experienced great growth in recent years, becoming one of the most important economic activities in the

world (Asche et al., 2022). Moreover, a major contribution of aquatic resources from aquaculture is expected in the future (Fiorella et al., 2021) since capture fishing has stabilized at levels that are practically impossible to overcome (Gephart et al., 2023). In addition to this, the growing demand for fish (FAO, 2022a), together with global population growth, which is about to reach the milestone of 10 billion people (FAO, 2020), requires that aquaculture activities be developed efficiently and sustainably in order to achieve global food security.

Globally, aquaculture reached a record of 122.6 million tons in 2020, which represents a value of USD 28.5 billion, and is estimated to grow by 13% in 2030 (FAO, 2022b). In 2022, aquaculture provided 50% of the total fish for direct human consumption in the world, being the Asia-Pacific region the major producer (Bartley, 2022). Regarding the diversity of cultivated species, macroalgae currently represent the largest production (51.3%), followed by mollusks (27.4%), crustaceans (9.1%), and other aquatic animals (0.6%) (Chopin and Tacon, 2021). It is important to highlight that modern aquaculture has developed to an advanced technological level that can be extended to all types of ecosystems (Goswami et al., 2023). But it must be recognized that most of the worldwide aquaculture operations are highly dependent on the environment and ecosystem performances (Pailan and Biswas, 2022). Despite this, traditional aquaculture, which is mainly developed in the form of monocultures Park et al. (2018), is disturbing these environments to such a degree that in many regions the activity has been affected to nearly disappear (Han, 2002; Thomsen et al., 2020). Therefore, the current global trend is developing strategies aimed at reducing the impacts of aquaculture to conserve natural capital, thus making it an environmentally friendly, efficient, profitable, and socially beneficial activity (Buschmann et al., 2001).

In Peru, aquaculture is sustained on monoculture: *Argopecten purpuratus* (36.4%), *Oncorhynchus mykiss* (34.2%), and *Litopenaeus vannamei* (24.2%) (PRODUCE, 2022). Here, the culture of the mollusk *A. purpuratus* notoriously outstands in the bays of Sechura and Samanco, which in 2018, with a production of 89,872 t, ranked 1 in Latin America and 4 in the world (Kluger et al., 2018). During the 20th century, aquaculture development has been characterized by intensive monospecific cultivation, based on species of high commercial value and high economic benefit. However, this aquaculture approach generates an important ecological footprint due to the organic waste produced in the cultivation and processing stages, threatening the integrity of ecosystems and the future viability of the sector (González Henríquez et al., 2015). As a result, aquaculture is often associated with pollution (Vela and Ojeda, 2007).

For producers, it is necessary to find measures that are compatible with profitability, as well as sustainability. In addition, it is imperative to migrate from traditional monoculture practices to integrated and sustainable models (Chopin, 2013), in order to ensure the continuity of the aquaculture activity. Under this need, the ecosystem approach to aquaculture (EAA) concept has emerged, which is considered as a strategy aimed at integrating the activity into a broader ecosystem that articulates sustainable development, equity, and resilience of interconnected socio-ecological systems (Brugère et al., 2019). In this sense, associating two or more species from different trophic levels is the most optimal way to reduce the environmental impacts of aquaculture.

This aquaculture approach has the advantage of not generating competition among the organisms in captivity, and additionally, improving the flow of matter and energy in the culture. Therefore, the worldwide trend is to implement integrated multi-trophic aquaculture (IMTA) (Chopin et al., 2001; Buschmann et al., 2013).

The IMTA represents the integration of four types of aquaculture: a) feed (fish), b) organic extractive (filter-feeding and suspension-feeding invertebrates), c) inorganic extractive (macroalgae), and d) deposit extractive (suspension-feeding and sediment-feeding invertebrates) (Chopin et al., 2001; Chopin, 2010; Chopin et al., 2010). Nevertheless, to integrate them it is necessary to establish the proportion between the species, according to their specific roles and the abiotic conditions of the ecosystem. This approach is addressed to maximize the benefits of different trophic levels, diversifying the activity, ensuring environmental sustainability and economic viability, while also improving the aquaculture image across society (Salinas-Morrondo, 2012).

The application of IMTA has been successful in several regions. In China, IMTA has been developed in coastal inlets integrating the culture of *Chlamys farreri*, *Crassostrea gigas* and *Laminaria japonica*, allowing them to estimate the exploitation load capacity of *C. farreri* and *C. gigas* in bays and the harvest potential, demonstrating that it is possible to control phytoplankton abundance by managing the density of extractive species (Buschmann et al., 2008b). In Dalian (China), the potential of the marine sponge *Hymeniacidon perleve* has been investigated, revealing a removal capacity between 44-61% of total organic carbon (TOC) in IMTA in co-culture with the marine fish *Fugu rubripes*, and also determining an increase in sponge biomass of 22.8% (Fu et al., 2007). Moreover, in Canada, it has been integrated macroalgae Laminariales and mussel *Mytilus edulis* into the culture of Atlantic salmon in cages, observing that the algae and mussels grow 50% faster than in control sites, proving that the food and nutrient residues generated in the cages have economic potential (Chopin and Robinson, 2004). In that sense, macroalgae can remove dissolved N between 35-100% (Thomas, 2010).

Under the scope of improving aquaculture in accordance with world trends, it is necessary to introduce the IMTA concept in order to be applied in the *A. purpuratus* cultures developed in Peru. Therefore, the purpose of this work is to present the problems of marine aquaculture in Peru and to develop the concepts and advantages of the IMTA model. This model is vital for the continuity *A. purpuratus* culture in Samanco Bay, in addition to providing other economic advantages for the aquaculture producers. The model presented here is also suitable for application to other types of aquaculture cultures in other regions of the world.

2 Aquaculture problems in PERU

2.1 Context of the *A. purpuratus* culture in Peru

The culture of this filter-feeding species is successful due to the high phytoplankton productivity of the Peruvian coast (Guillén and Rondán, 1968). Cultivation is performed in bays such as Sechura,

Nonura, Lobos de Tierra (Piura region), Samanco, Guaynuma, Los Chimus, Salinas, Tortugas, Casma (Ancash region), Independencia, and Paracas (Ica region). In total, the culture of *A. purpuratus* is developed in around 15,999.67 ha, corresponding to 374 rights in modalities of Micro and Small Enterprise Aquaculture (AMYPE, <150 t, 82%), Medium and Large Enterprise Aquaculture (AMYGE, >150 t, 18%) and Aquaculture of Limited Resources (AREL, <3.5 t, <1%) (PRODUCE, 2021). The main form of culture is performed in suspended lines with longline systems, but corrals under the seabed are also used by small-scale producers.

Suspended cultivation is practiced in long-line systems of 100 m, located at a depth of 6 m. Here, lanterns of 2 m in height and 0.5 m in diameter are suspended in the long line systems every 1 m. As a general rule, 3 lines are installed in 1 ha, which remains immovable. The growth process lasts between 12-14 months, and the final phase is carried out at a density of 250 organisms per lantern, employing approximately 49.2 million organisms in 1000 ha approximately. In the final stage of culture, *A. purpuratus* is harvested at 106.5 ± 23.6 g each.

The evolution of the *A. purpuratus* culture shows two stages (Figure 1): a slow growth between 1996-2009, and a fast growth from 2010 onwards. The latest is explained mainly by the formalization of a large number of fishermen's associations that were previously considered informal and were not recorded in the statistics at that time. Notably, the 2010-2018 period is characterized by great instability due to massive mortalities of cultured organisms in Sechura Bay, associated with oxygen deficiency due to harmful algal blooms (HAB) (Gonzales and Yopez, 2007; IMARPE, 2019), the occurrence of El Niño event, such as the one in 2017 (Salazar Camacho, 2023), and deficiencies in the supply of seed from the natural environment.

Despite this, the activity generated more than 10,162 new jobs in 2019 (PRODUCE, 2020), and incomes of USD 420.7 million in 2021, from exportation (PRODUCE, 2022), contributing foreign exchange to the country. Although the economic advantages of this activity are significant, it has also caused serious problems derived from organic contamination, with repercussions on water quality, eutrophication, and impacts on benthic biodiversity. Thus, this activity is clearly not aligned with the principles of sustainability and, if not accounted for, could restrict the continuity of the activity

in the medium to long term. In addition, it will have repercussions on other economic value chains, small producers, and the recreational landscape of the bays.

2.2 Environmental impacts of *A. purpuratus* culture in Samanco Bay

The production process generates impacts due to: a) ammonia excretion products from cultured organisms and biofouling, b) biodeposition (feces and pseudofeces) by *A. purpuratus* and biofouling, and c) disposal of biofouling *in situ*, due to bad practices, not yet quantified (Loayza Aguilar, 2018). Further contamination is contributed by the disposal of lines, buoys, lanterns, and perl net (broken or unusable), not yet quantified as well.

Biofouling represents the main source of contamination during cultivation. This is composed of algae and invertebrates that develop attached to the culture structures (lanterns, lines, buoys, floating structures). It has been estimated that in the final phase of culture, a lantern can produce between 68.04 to 131.87 kg of biofouling (Loayza and Tresierra, 2014; Loayza Aguilar, 2018). The filter-feeding species *Semimytilus algosus* and *Ciona intestinalis* have been identified as the main biofouling components, which account for 58.6 to 73.0 and 22.3 to 50.0% of the biofouling per lantern, respectively (Loayza Aguilar, 2018). Likewise, Uribe et al. (2008) and Uribe and Blanco (2001), reported that in Tongoy Bay (Chile), a lantern can produce between 100 to 120 kg of biofouling every 3 months. These data show the magnitude of impacts by *A. purpuratus* cultivation.

Besides, feces and pseudofeces are produced by *A. purpuratus* in conjunction with the biofouling organisms represent an important source of pollution. These pollutants release NH_4 , NO_3 , and PO_4 , which are initially deposited in the water column and then distributed throughout the environment by the effect of marine currents (Buschmann et al., 2001), promoting primary productivity. The release of feces and pseudofeces also promotes the biodeposition of organic matter (OM) in the water column, decreasing transparency. In addition, these particulate residues precipitate to the seabed where they accumulate and modify the granulometric composition of the substrate. This has proven to be the main source of sludge

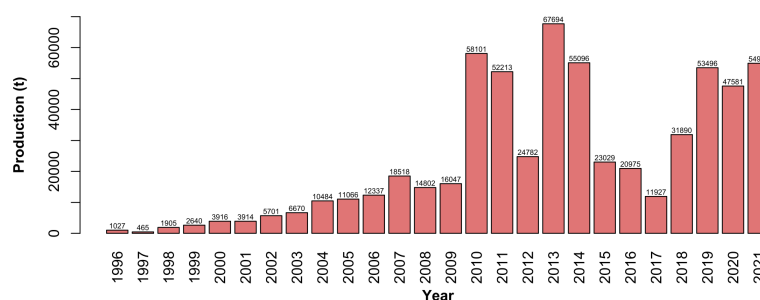


FIGURE 1

Production of *A. purpuratus* from aquaculture in Peru, during the period 1996 to 2021 (Cavero and Rodríguez, 2008; PRODUCE, 2015; PRODUCE, 2020; PRODUCE, 2021; PRODUCE, 2022). The production of *A. purpuratus* had an important growth since 2010, however, due to extraordinary events, such as the El Niño phenomenon, in 2012 and during the period 2015-17, the production declined significantly. The production remains sustained in the last years despite environmental concerns.

generation at the bottom of the bays. As a consequence, a decrease in dissolved oxygen in the marine environment has been observed, with the release of toxic substances such as H_2S and NO_2 . Naturally, biodiversity and natural banks of interest to small-scale fishing are significantly affected. On the subject, there are no data on the rates of biodeposition and excretion of NH_4 from *A. purpuratus* and biofouling, or about the production of NO_3 and PO_4 by bacterial action, which we could have a deeper understanding of their impacts.

Regarding the impact of biodeposition, assuming the biodeposition rate recorded in Tongoy Bay (Chile) of 3.9 times the weight of the organisms (Uribe and Blanco, 2001), we can estimate that Samanco Bay would be producing 5,239.8 t in feces and pseudofeces every 12–14 months. This unavoidable quantity, directly related to production volumes, is of great concern, considering that dissipation in the bay is slow according to the currents. Biofouling biodepositions (due to detachment) should be added to this, although due to lack of information, it is not possible to provide accurate estimations.

Among other impacts, we have the disturbance of the benthic ecosystem. Herein, a key aspect to consider is the calcareous valves that are deposited on the seabed, which quantities have not yet been quantified. However, it is known that 67% of the biomass of *A. purpuratus* is composed by valves (Loayza Aguilar, 2018). The valves cause capping of the substrate, trapping of OM, and increase bacterial activity on the seabed. This event drives an exacerbated production of H_2S and NO_2 , limiting oxygen exchange at the water-sediment interface (anoxic conditions). Studies have been conducted to reduce biofouling production bacteria (Colunche Díaz et al., 2016) and doubling lantern exchange (Loayza Aguilar, 2018), but remain as proposals.

The organic matter released also encourages the eutrophication of the bay. Excessive phytoplankton biomass reduces water transparency and it sediments to the bottom when is not consumed, increasing OM and therefore a microbial activity that demands oxygen in specific areas referred to as “dead zones”. This obviously alters the diversity in the water column and on the seafloor (Buschmann et al., 2008b; Buschmann et al., 2009; Chopin et al., 2012), causing mortality of benthic-demersal and pelagic resources as reported in Sechura Bay in 2019 (IMARPE, 2019). In addition, nutrients promote excess biomass of macroscopic algae, with increased OM decomposition and repercussions on fisheries, and loss of the landscape value of the coasts (Camargo and Alonso, 2007; Buschmann et al., 2008b) This is related to the exuberant production of macroalgae in the bay, such as *Caulerpa filiformis* and *Ulva* spp. which, by accumulating on the beaches, affect the habitat and the intertidal and subtidal benthic community, affecting fishery resources such as *Donax marincovichii*, *Emerita analoga*, and others of ecological importance, such as *Excirolana braziliensis* and *Lepidopa chilensis*, which are food for seabirds.

2.3 Water and sediment quality in Samanco bay

Due to the importance of the aquaculture activity, studies on water and sediment quality are conducted periodically in Samanco

Bay. The following tables present the 13-year historical evolution of the conditions concerning water quality and sediment (Tables 1, 2), and those of the *A. purpuratus* culture concession area (Table 3), compared to the Environmental Quality Standards (EQS) for Water (MINAM, 2017), and the standards of the Canadian Environmental Quality Guidelines (Guidelines CEQ, 1999).

Oxygen in the water column tends to increase, exceeding EQS category 2C1 values (Table 1), which can be attributed to a process of eutrophication, linked to an accumulation of nutrients (N and P) due to bacterial mineralization of biodepositions and biofouling in the concession area. Two aspects characterize eutrophication: a) dissolved P is present in excess and dissolved N (NH_4 , NO_2 , and NO_3) near or below detection levels (Ryther and Dunstan, 1971), and b) levels above 440 μg NT l (0.44 mg l) and 30 μg PT l (0.03 mg l), can generate eutrophication in coastal areas (Swedish, 2000). As shown in Table 1, P is 2.68 to 6.15 times higher than EQS, and is no longer a limiting factor for phytoplankton productivity, hence any excess of N will stimulate eutrophication.

A study evaluated the behavior of oxygen for the period 2013–18, in one of the companies dedicated to the production of *A. purpuratus* in Samanco Bay, encountering 2.8 ± 0.96 mg l⁻¹ at the bottom (16 m) (Ramos Alfaro and Villegas Ruiz, 2019). This coincides with the data for the periods 2005–10 and 2014–15 (Table 1). As these values are below the EQS category 4E3, benthic community organisms, including those of artisanal fishing, would be affected, with social and economic repercussions for the fishing community. In the cultivation area, OM (Table 3) was between 1.48 and 2.71 times higher than in the rest of the bay (Table 2), confirmed by IMARPE (IMARPE, 2009b) and OEFA (OEFA, 2013), that found values of 7.18% in 2000, 28.17% in 2008, and 20.8% in 2012, with respect to the baseline of 2.14%. In addition, for the period 2013–18, it has been reported that sediment from the cultivation area of one of the companies dedicated to the production of *A. purpuratus* was characterized by fine-black sludge with a sulfurous odor, and in 75% of the biannual samplings, no live organisms were recorded, but empty shells of *S. algeosus* and *A. purpuratus* were found (Ramos Alfaro and Villegas Ruiz, 2019). These characteristics are related to the concentration of 279 mg kg⁻¹ of H_2S found in 2013 by OEFA (2013), a value 266 times higher than that reported in the baseline (1.05 mg kg⁻¹). These findings demonstrate the impact that the culture exerts, altering not only the chemical and granulometric composition of the sediment but also benthic biodiversity and abundance, including some fishery interest, as *A. purpuratus* cultures, as well as socio-economic repercussions, in addition to the economic profitability of the company (Figure 2).

The accumulation of biodepositions, biofouling, and phytoplankton biomass on the bottom of Samanco Bay would be increased by the resistance of the anchoring system of the cultivation lines (700 kg weight and 1 m height), from operational and abandoned concessions to the velocity of the bottom currents, retaining OM and calcareous valves. On the other hand, cultivation operations are carried out in approximately 65% of each concession, which implies the use of roughly 196,800 lanterns, which generate a field of resistance to the current velocity, and therefore an increase in the sedimentation velocity of the seston generated by the cultivation, contributing to the accumulation of OM on the seabed.

TABLE 1 Physico-chemical parameters of water in Samanco Bay during the period 2005-10, 2014-15, and November 2018.

Parameter	Surface	Middle	Bottom	Quality standard
Dissolved oxygen (mg l⁻¹)				
2005-10*	7.66 ± 1.23	No data	2.85 ± 1.22	EQS categories 2
2014-15**	8.40 ± 0.75	4.77 ± 0.47	4.19 ± 0.81	and 4 (≥ 4 mg l ⁻¹)
November 2018***	8.52	8.31	5.60	
Nitrates (mg l⁻¹)				
2005-10*	0.343 ± 0.283	No data	No Data	EQS categories 2
2014-15**	<EQS	<EQS	<EQS	(16 mg l ⁻¹) and 4
November 2018***	0.130	0.085	0.240	(200 mg l ⁻¹)
Phosphates (mg l⁻¹)				
2005-10*	0.288 ± 0.203	No data	0.381 ± 0.192	EQS categories 2
2014-15**	0.056 ± 0.001	0.099 ± 0.002	0.086 ± 0.004	and 4 (0.062 mg l ⁻¹)
November 2018***	0.135	0.130	0.166	
SST (mg l⁻¹)				
2005-10*	31.37 ± 7.83	No data	30.30 ± 8.87	EQS categories 2
2014-15**	20.55 ± 2.32	19.02 ± 0.52	19.81 ± 4.72	(80 mg l ⁻¹) and
November 2018***	12.55	No data	12.95	4 (≤ 30 mg l ⁻¹)

Data source: *García et al. (2013), **García et al. (2015), ***García Nolasco et al. (2019). Environmental Quality Standards (EQS) for Water (MINAM, 2017).

There are few studies on the impacts of biodeposition from shellfish culture. In Canada, Richard et al. (2007), observed the accumulation of feces and pseudofeces in the *M. edulis* and *Placopecten magellanicus* culture area were twice as high as in the control area, and the abundance of benthic macrofauna was 6 times lower than in the control area. Heavy metals such as Cd, Pb, Cr, As, and Hg in marine sediments are of concern because they bioaccumulate and biomagnify, with high toxicity (Sadiq, 2021), and affect communities (Kennish, 2002), biogeochemical cycles (Sadiq, 2021), and humans who use them in their consumption. In hydrodynamically stable environments, such as Samanco Bay, heavy metals have a strong affinity for finer sediments (Calderón and Valdés, 2012), such as clay, humic acid, OM, Fe, Mn, and CaCO₃ oxides, capable of forming complexes with metal ions and being adsorbed (Kennish, 2002; Sadiq, 2021). Deep-sea currents, waves, storms, and activities such as dredging, shipping, and commercial fishing can resuspend heavy metals (Kennish, 2002), and re-enter in food chains.

In Samanco Bay, the sources of heavy metals (Table 2) may be lixiviated from the bedrock area and contributions from the Nepeña River, which irrigates 9,000 ha of agricultural land (ANA, 2009), and its flows discharge in the southeastern part very close to the mouth of the bay (García Nolasco et al., 2019). This river has a small discharge, however, during El Niño events, it has a great influence and may be transporting As, Se, Ba, Cd, Cr, Pb, Hg, and Ag, pollutants that may come from agricultural and livestock farming activities (Metcalf and Eddy, 1995), especially Cd that is an ingredient of phosphate fertilizers (Arnous and Hassan, 2015). The values of Cr, Cu, and Pb in sediments in the bay (Table 2) and within the marine cultivation area are below the Interim Sediment Quality Guideline (ISQG) and Probable Effect Level

(PEL); however, As, Cd and Hg are at risk levels, since in the sediment outside the marine concessions they represent, respectively, 9.55, 3.33 and 1.31 times the ISQG, and within the concessions 3.2, 8.27 and 2.62 times, respectively, the ISQG. It is advisable to study the dynamics of these metals in sediments, water, and the bioaccumulation and biomagnification in the biota of Samanco Bay, and in the organisms in culture.

Due to its biological, bathymetric, and marine dynamic qualities, Samanco Bay is suitable for greater development of mariculture. The diagnosis made in previous paragraphs reveals that it urgently requires a new approach. It should focus on two fundamental aspects: a) within the scope of the General Aquaculture Law which invokes two principles: (a1) sustainability, e.g. profitable and competitive aquaculture, but in harmony with the conservation of resources and the ecosystem, which guarantees the satisfaction of the necessities of future generations, and (a2) the ecosystem approach, which considers the environmental, social and institutional dimensions, which encourages equity in the distribution of benefits, respect for the integrity and functionality of ecosystems; and, (b) adopt technologies to satisfy these principles, through the IMTA concept.

3 Integrated multi-trophic aquaculture (IMTA)

3.1 Foundations of the IMTA model

Integrated multi-trophic aquaculture (IMTA) involves the culture of two or more aquatic species from different trophic levels to improve efficiency, reduce waste and provide ecosystem

TABLE 2 Organic and inorganic water pollution in Samanco Bay during the period 2005-10, 2014-15, and November 2018.

Parameter	Surface	Middle	Bottom	Quality standard
Organic matter (%)				
2005-10*	2.26	4.49	3.77 ± 0.57	
2014-15**	4.15	9.82	6.89 ± 2.24	No standard
November 2018***	No data	No data	4.83	
Heavy metals				
Arsenic (mg kg⁻¹)				
2005-10*	10.95	155.73	69.13 ± 69.36	ISQG (7.24 mg kg ⁻¹), PEL (41.6 mg kg ⁻¹)
Mercury (mg kg⁻¹)				
2005-10*	0.12	0.32	0.17 ± 0.08	ISQG (0.13 mg kg ⁻¹), PEL (0.70 mg kg ⁻¹)
Cadmium (mg kg⁻¹)				
2005-10*	0.23	2.54	1.19 ± 0.74	ISQG (0.7 mg kg ⁻¹), PEL (4.2 mg kg ⁻¹)
2014-15**	0.68	5.04	2.33 ± 1.46	ISQG (0.7 mg kg ⁻¹), PEL (4.2 mg kg ⁻¹)
Chromium (mg kg⁻¹)				
2014-15**	19.13	29.76	23.44 ± 4.15	ISQG (52.3 mg kg ⁻¹), PEL (160 mg kg ⁻¹)
Cooper (mg kg⁻¹)				
2005-10*	29.43	37.65	35.06 ± 2.93	ISQG (18.7 mg kg ⁻¹), PEL (108 mg kg ⁻¹)
2014-15**	0.68	5.04	2.21 ± 1.61	ISQG (18.7 mg kg ⁻¹), PEL (108 mg kg ⁻¹)
Lead (mg kg⁻¹)				
2005-10*	1.11	3.25	2.16 ± 0.97	ISQG (30.2 mg kg ⁻¹), PEL (112 mg kg ⁻¹)
2014-15**	3.69	13.39	8.78 ± 3.19	ISQG (30.2 mg kg ⁻¹), PEL (112 mg kg ⁻¹)

Data source: *García et al. (2013), **García et al. (2015), ***García Nolasco et al. (2019). ISQG (Interim Sediment Quality Guideline): concentration below which there is no adverse biological effect, and PEL (Probable Effect Level): concentration above which adverse biological effects are frequently encountered [Guidelines CEQ \(1999\)](#).

services, such as bioremediation FAO (2022). IMTA is the practice of combining, in appropriate proportions, the culture of fed aquaculture species (e.g. fish and shrimp) with organic extractive aquaculture species (e.g. shellfish and detritivores) and inorganic extractive aquaculture species (e.g. seaweed) (Sasikumar and Viji, 2015). The IMTA's goal is to create balanced systems for environmental sustainability (biomitigation), economic stability (product diversification and risk reduction), and social acceptability (best management practices). Currently, IMTA is an appropriate method for developing economically viable and socially beneficial coastal aquaculture Hossain et al. (2022).

A fundamental aspect of developing the IMTA model is species selection. Careful consideration must be given to the suitability of species in a particular habitat/farming unit, and they must be economically viable as aquaculture products Sukhdhane et al. (2018). To this end, the following aspects are recommended for the selection of species in the IMTA model: a) the selected species must have complementary roles with the other species in the system, b) they must be species adaptable to the cultivation technologies and environmental conditions of the site, c) they must possess the capacity to provide efficient biomitigation, and d) market demand and an attractive price (Sasikumar and Viji, 2015).

3.2 Perception

Mariculture in the 20 century did not acknowledge that when the development of any economic activity exceeds natural limits, it implies the deterioration of ecosystems, which can be irreversible and hinder the permanence of the activity that originates them (Martínez and Roca, 2015). For instance, in the Bay of Fundy (Canada), the production of 35,000 t of salmon had an exogenous input of 1,225 t of N and 245 t of P, a load that is retained, since the residence time of the water within the bay is about 76 days (Chopin et al., 2007). At fish cage culture locations, N can be 1.8-2.3 times more compared to a control site (Wen et al., 2007), accumulate sediment within 100 m and elevate N and P by 8-25 times up to 1,000 m from the cages (Tolga et al., 2017), promoting eutrophication and affecting the resilient capacity of the ecosystem.

In view of the situation described above, a new approach is required, which contemplates the ecosystemic balance, using species of multiple trophic levels. The approach of culturing organisms as primary producers, filter feeders, detritivores, and carnivores in a defined area, allows the recycling of the waste produced, minimizing environmental deterioration, under a circular economy approach (Buschmann et al., 2013; González Henríquez et al., 2015; Correia et al., 2020). This brings us to the

TABLE 3 Water and sediment quality values in Samanco Bay during the period 2005-10, 2014-15, and November 2018.

Parameter	Surface	Middle	Bottom	Quality standard
Water				
Dissolved oxygen (mg l⁻¹)				
Surface	8.13	11.46	9.35	3*EQS categories 2 and 4 (≥ 4 mg l ⁻¹)
Middle	1.77	9.10	5.76	
Bottom	3.46	7.66	3.46	
SST (mg l⁻¹)				
Surface	3.60	49.60	19.27	EQS categories 2 (80 mg l ⁻¹)
Middle	2.40	24.40	15.01	and 4 (≤ 30 mg l ⁻¹)
Bottom	4.00	47.20	16.80	
Sediment				
Organic matter (%)	3.45	19.20	10.20	
Heavy metals (mg l⁻¹)				
Arsenic (mg kg ⁻¹)	0	48.3	23.16	ISQG (7.24 mg kg ⁻¹), PEL (41.6 mg kg ⁻¹)
Mercury (mg kg ⁻¹)	0	1.36	0.34	ISQG (0.13 mg kg ⁻¹), PEL (0.70 mg kg ⁻¹)
Cadmium (mg kg ⁻¹)	0	15.20	5.79	ISQG (0.7 mg kg ⁻¹), PEL (4.2 mg kg ⁻¹)
Chromium (mg kg ⁻¹)	10.46	61.70	32.42	ISQG (52.3 mg kg ⁻¹), PEL (160 mg kg ⁻¹)

Data source: *García et al. (2013), **García et al. (2015), ***García Nolasco et al. (2019). ISQG (Interim Sediment Quality Guideline): concentration below which there is no adverse biological effect, and PEL (Probable Effect Level): concentration above which adverse biological effects are frequently encountered [Guidelines CEQ \(1999\)](#).

point of addressing the IMTA concept, which guarantees the viability of aquaculture in the long term, generating social acceptability.

3.3 IMTA model proposal for Samanco Bay

The proposed IMTA model (Figure 3) is a design for environmental sustainability, and implies using cultures in proximity, with commercially valuable species of different trophic levels and with complementary ecosystemic functions, which synergistically act in the recycling and biomitigation processes

(Chopin et al., 2010; Chopin et al., 2012; González Henríquez et al., 2015). In this sense, the system would be integrated by: a) extractive aquaculture of organic suspension, which represents the production of *A. purpuratus*, b) extractive aquaculture of inorganic suspension, based on macroalgae, and c) extractive aquaculture of deposit, using holothurians (Figure 4). In this model, the OM (feces, pseudofeces, biofouling organisms) are disposed into the water by the main culture, and the nutrients released, such as N and P, are no longer contaminants as they are biotransformed into valuable resources by the other organisms.

As a result of the implementation of the IMTA model, we would have: biodiversity preserved, aquaculture diversified and

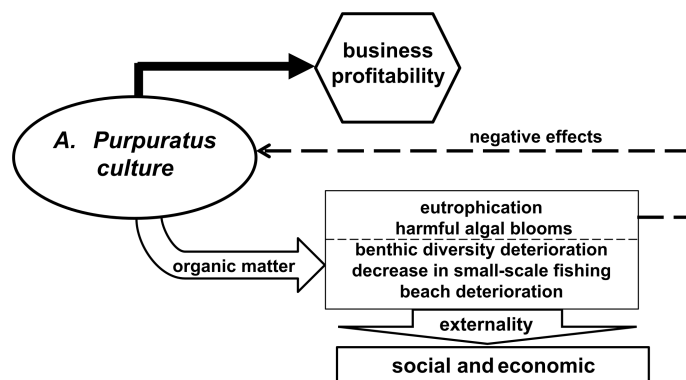


FIGURE 2 Traditional marine culture model in Samanco Bay.

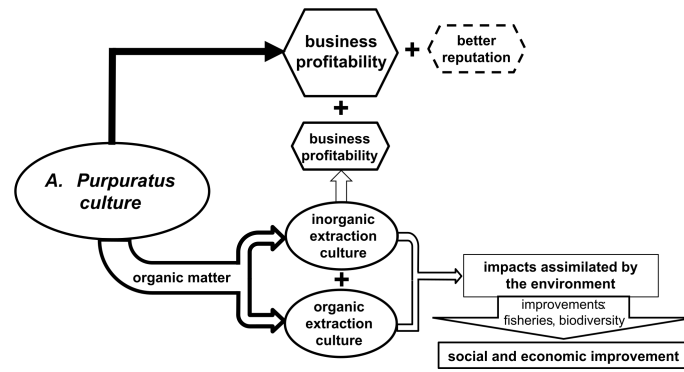


FIGURE 3 Proposed IMTA marine culture model for Samanco Bay.

profitability improved, as the proposed biotransformer species have current or potential economic value (Table 4). As an additional advantage, the main culture will be more efficient by reducing the impacts of eutrophication and HAB, and therefore more profitable. These advantages are transferred to the ecosystem, since, as less OM reaches the bottom and the accumulated is used by the organisms in the benthic system; therefore, the artisanal fishing activity and the balneability of the summer beaches would be recovered. This translates into social benefits for the activity, thus improving its image in society. This principle, which is practiced on a commercial scale mainly in China, improves the sustainability of the aquaculture systems, clearly reducing environmental risks and increasing profits (Han et al., 2016).

It is worth mentioning that, in the IMTA context, marine macroalgae are an indispensable and mandatory component to solve nutrient accumulation, since they constitute the primary organisms that require solar energy and sequester C, N, and P from the environment (Neori et al., 2004). In this sense, its great bioremediation capacity is highlighted. (Buschmann et al., 2013). The best criterion for choosing algal species for integration into the

IMTA is to combine commercial value with high growth rates and N concentration in their tissues (Neori et al., 2004).

On the other hand, holothurians or sea cucumbers as deep-sea extractive organisms, act as nutrient recyclers and bioturbation agents, allowing bottom oxygenation and preventing OM stratification. Hence, their participation is indispensable for the management of marine ecosystems (Han et al., 2016; Tolga et al., 2017), and enhances the detrimental effects of coastal mariculture (Purcell et al., 2012).

An aspect of relevance in terms of economic value is related to the internalization of nutrient removal costs. This is aimed at encouraging the development of technologies to reduce environmental threats (Buschmann et al., 1996; Neori et al., 2007; Buschmann et al., 2008a; Buschmann et al., 2013), and political strategies, such as the idea of developing N bonds, as is currently practiced in the municipality of Lysekil (Sweden), which pays USD 10 kg of N extracted by *M. edulis*. Furthermore, the creation of incentives for cultivation under the IMTA model can be a policy that promotes the recovery of disturbed environments (Buschmann et al., 2008a) especially in Samanco Bay.

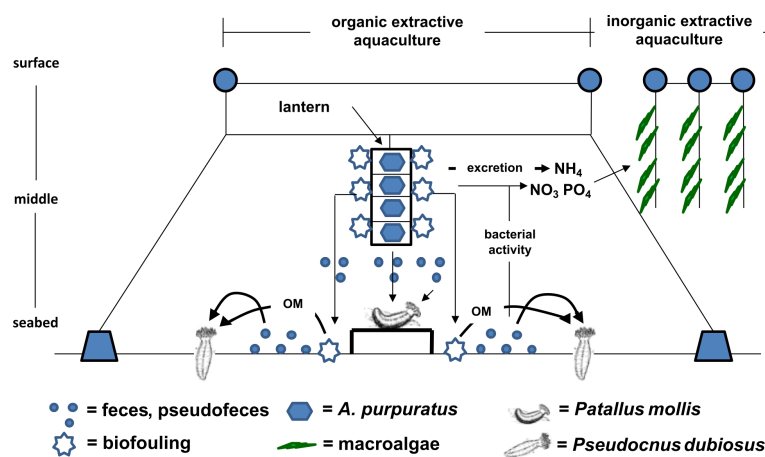


FIGURE 4 Diagram of the IMTA model proposed for experimental assays in Samanco Bay.

TABLE 4 Components of the IMTA and local candidate species for cultivation in Samanco Bay.

Aquaculture type	Commercial expectations
Organic extractive in suspension	
Bivalve molluscs	
<i>A. purpuratus</i>	Known and secure foreign market
Inorganic extractive in suspension	
Macroalgae	
<i>Chondracanthus chamosoi</i>	Human consumption (IMARPE, 2009a; Saavedra et al., 2019; Avila-Peltroche and Padilla-Vallejos, 2020) and carrageenan (Buschmann et al., 2001; Avila et al., 2011)
<i>Porphyra columbina</i>	Human consumption (Romo et al., 2005; Avila-Peltroche and Padilla-Vallejos, 2020)
<i>Gracilariopsis lemaneiformis</i>	Agarophyte (Ramírez and Tapia, 1991; Pang et al., 2010)
<i>Ulva lactuca</i>	Potential feed input for <i>Lipenaeus vannamei</i> , terrestrial animals (Villalobos, 2012), <i>Macrobrachium rosenbergii</i> (Felix and Brindo, 2014), human food ("anori" in Japan) (Bolton et al., 2009), aquaculture feed, IMTA pilot systems (Bolton et al., 2009), biomass energy, bioactive principles (Coste et al., 2015), potential food for cultivation of herbivorous aquatic species
Organic extractive deposit	
Holothurids	
<i>Patallus mollis</i>	Human consumption (Uribe et al., 2013)
<i>Pseudocnus dubiosus</i>	Potential alimento para aves, sustancias anticancerígenas (Ruzafa and Diego, 1985)

3.4 Conclusion

The industrial cultivation of *A. purpuratus*, in Samanco Bay, has generated jobs and related activities that stimulate the local economy and contribute to foreign exchange in Peru. However, it is being developed under a classic model (monospecific cultivation), prioritizing economic profits with almost no environmental responsibility. We anticipate that if this situation persists, it could exacerbate the impacts on the ecosystem, but at the same time generate inadequate physical and chemical conditions for the sustainability of the activity itself.

The proposed IMTA model has great potential to be an economically much more profitable activity, but in a balanced ecosystem, for which it is necessary to adopt this new production model with an ecological engineering approach. The integration of species from different trophic levels is the key concept for their adaptation. This model will allow them to diversify their production, improve their economic and social profitability, and guarantee their sustainability.

Finally, we consider that the adaptation of the proposed model will not be an effortless task. The main challenges will be the technological adaptation in addition to government policies that encourage the transition to an IMTA model. It will also be necessary to study the physical and chemical characteristics of the water mass, oceanographic dynamics, physical and chemical description of the bottom, and a better understanding of the socioeconomic conditions for businesses. It is therefore imperative to involve academia, the competent authority, and the business community.

Author contributions

RL-A conceived the idea, conducted the research, obtained the grant, wrote the original draft, edited, revised, and supervised the work. YH-P investigated, wrote, reviewed, edited, and administrated the project. GS-R investigated, wrote, edited, reviewed, and supervised the work. GO-R reviewed, wrote, edited, and produced the images. All authors contributed to the article and approved the submitted version.

Funding

This work was funded by the PNIPA-CU-SFOCA-PP-000045 Subproject "Capacity building for the management of multi-trophic crops in Samanco Bay (Ancash, Peru)", Contract N° 021-2018-PNIPA-SUBPROYECTOS.

Acknowledgments

We would like to express our gratitude to the Vicerrectorado de Investigación at Universidad Nacional del Santa (VRIN-UNS), who supported us in the publication process.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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