

Biofouling reduction by lantern nets exchange and its relationship with production and survival of *Argopecten purpuratus* in Samanco Bay, Peru

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Abstract

The aquaculture of *Argopecten purpuratus* (Peruvian scallop) is a profitable activity with positive impacts on the local economy. However, the development of biofouling on the culture lantern nets generates negative environmental impacts that affect its sustainability. A feasible option aimed at reducing the development of biofouling is to increase the frequency of lantern nets exchange. In this study, we tested whether doubling the lantern net exchange frequency in the final phase of culture reduces biofouling and, in turn, improves the growth and survival of *A. purpuratus*. For this purpose, in the concession of a company dedicated to the cultivation of *A. purpuratus* in Samanco Bay, Peru, four 10-floor lantern nets were placed at 25 organisms per floor, divided into two treatments (T1 and T2) with two replicates. One group of these (T1) was exchanged after 30 days, and another group (T2) was maintained until harvest. As a result of the lantern nets exchange, biofouling weight was reduced by 64.6%, survival improved by 10.8%, gonad weight increased by 52.5%, and adductor muscle weight increased by 62.4%, which represents an additional net income of 6582.58 US\$ per ha. This study demonstrates the significant benefits of regular lantern net exchanges in mitigating biofouling and enhancing the overall yield and

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economic viability of *A. purpuratus* culture, contributing to the advancement of more sustainable aquaculture practices.

KEYWORDS

Argopecten purpuratus, biofouling, lantern nets, marine cultivation, profitability

1 | INTRODUCTION

In 2020, global aquaculture reached a production of 122.6 million tons, with a value of 281.5 billion US\$, having registered a growth of 14.5% over 2019 (FAO, 2022). In the near future, aquaculture's contribution to human development will be fundamental because it is estimated that by 2050 the world population will reach 9.6 billion people (FAO, 2014). This contribution will be more relevant in poor and emerging countries as it will provide food, jobs, and incomes from outside the country.

The Peruvian coast is one of the most productive in the world (Kiel et al., 2023). Here, since 1979, mariculture has been developed in bays such as Sechura, Lobos de Tierra, Samanco, Tortugas, Independencia, and Paracas (Valdivia & Benites, 1968), where the most cultivated species is *Argopecten purpuratus* (Peruvian scallop), a bivalve that filters suspended particles (siston), mainly phytoplankton (Avendaño et al., 2001; Rouillon et al., 2002; Shumway & Parsons, 2016). In 2022, Peru recorded 15,643.2 ha in *A. purpuratus* production, harvesting 26,505.4 t, which represented an export income of more than 102 million US\$ FOB. Here, the main productive bays are Sechura and Samanco Bay; the latter had a production of 8731.25 t in the same year (PRODUCE, 2022.).

To start the cultivation process, it is needed to obtain seeds of *A. purpuratus* (larvae) either through the collection from natural banks or through reproduction in laboratories (hatcheries). In the hatcheries, reproduction begins with the selection of breeders, gonadal maturation, spawning induction, fertilization, and larval development (Crisóstomo et al., 2024). Subsequently, the seeds are transported for cultivation to the sea. The cultivation of *A. purpuratus* is primarily conducted in suspended “long line” systems, which have proven to be an effective alternative for optimizing exposure to marine currents and ensuring a continuous supply of nutrients (Zhao et al., 2019). In these systems, cultivation lines approximately 100 m in length are deployed, along which specific structures—known as cultivation lanterns (typically 2 m in height by 0.5 m in width)—are attached to support the organisms. Typically, three fixed lines per hectare are installed, enabling a final cultivation density of 250 organisms per lantern, which corresponds to approximately 49.2 million individuals per 1000 hectares. The growth process spans 12–14 months and culminates with the harvest of specimens weighing an average of 106.5 ± 23.6 g (Loayza-Aguilar et al., 2023). This infrastructure facilitates efficient management and monitoring of the cultivation system.

This activity generates many benefits, such as jobs; stimulates the local economy; and generates great foreign exchange because almost all of the product is exported. However, it also generates negative impacts, including biofouling, which develops on lines, cords, buoys, and platforms, but more intensely on the cultivation lantern nets, impacting economic profitability and the environment (Loayza-Aguilar et al., 2023). Biofouling refers to any form of life that adheres to and develops on artificial surfaces submerged under water (Cao et al., 2011), composed of opportunistic species that form calcareous shells (barnacles, mussels, tubeworms, bryozoans, and corals) and other soft-bodied species (algae, hydrozoans, sponges, or ascidians) (Dobretsov & Miron, 2001). For instance, in Tongoy Bay (Chile), a cultured lantern net can reach 120 kg of biofouling (Uribe & Blanco, 2001), and in Samanco Bay, in 2–3 months, 68.04 kg (summer) to 73.42 kg (winter) is generated (Loayza & Tresierra, 2014); therefore, this constitutes a concerning issue in the industrial cultivation of *A. purpuratus*.

In Samanco Bay, biofouling causes negative impacts due to its high-density development on the culture lantern nets of *A. purpuratus*. The organisms that constitute biofouling compete strongly for food and limit water flow into the lantern net, basic requirements for proper growth of *A. purpuratus* (Loayza-Aguilar et al., 2023). They also cause physiological stress to cultured bivalves, leading to apoptosis and other undesirable states (Feidantsis et al., 2023). In addition, the production of feces and pseudofeces by biofouling organisms increases suspended solids and results in higher biochemical oxygen demand (BOD), promoting bacterial activity. Likewise, the deposit of feces and pseudofeces from the lantern nets into the water column reduces transparency and further increases the BOD, and, by sedimentation, part of this organic matter reaches the bottom (Fowler & Knauer, 1986; Uribe & Blanco, 2001), changing the granulometric composition and thus increasing the concentration of organic matter, affecting benthic biodiversity (Berrú & Tresierra, 2007). This problem is exacerbated by bad practices when biofouling is dumped at sea; it is estimated that approximately 20% of the biofouling is disposed of in the water (Tapia-Ugaz et al., 2022). Upon reaching the bottom, they incorporate organic matter and calcareous shells, contributing to further changes in the substrate composition (Lacoste & Gaertner-Mazouni, 2014). To this end, bacterial activity generates hypoxia or anoxia conditions, with the release of hydrogen sulfide (H_2S) and nitrogen dioxide (NO_2) of toxic character (de Miguel-Fernández & Vázquez-Taset, 2006; Filipovic et al., 2018; Godoi et al., 2018). Moreover, bacterial activity produces ammonium (NH_4), nitrates (NO_3), phosphates (PO_4), and sulfate (SO_4), nutrients that, upon reaching the photic zone, encourage eutrophication. Furthermore, if we consider economic aspects, the increased weight of the lantern nets leads to higher operating and maintenance costs (Aarnes et al., 1990). This is due to the expense involved in tasks such as re-hoisting the lantern nets, moving them to maintenance sites, cleaning them, and managing the significant amount of waste when disposing of them on land.

This has led to certain measures being proposed to alleviate the biofouling problem. Using biological controllers, *Echinometra lucunter* (rock boring urchin) and *Lytechinus variegatus* (green sea urchin), it was possible to reduce biofouling in lantern nets in a pilot culture of *Nodipecten nodosus* (lion's paw scallop) in Nenguange Bay, Colombia, by up to 68%, evidencing an increase in size and greater survival (Cortés-Useche et al., 2011). There are other assays to limit biofouling development by applying mechanical, chemical, biochemical, and biological strategies (Pérez et al., 2006; Qian et al., 2001; Vladkova, 2007), but they are still inconclusive or not applicable due to their toxicity (Cao et al., 2011). On the other hand, coating lantern nets with copper- and heavy metal-free antifouling paint resulted in a 30% decrease in biofouling abundance and a 4.9% reduction in *A. purpuratus* mortality (Colunche Díaz et al., 2016). Locally, there are only reports on the biodiversity of biofouling in the culture of *A. purpuratus* (Encomendero et al., 2006; Loayza & Tresierra, 2014; Pacheco & Garate, 2005; Tapia, 2000), but there are no effective techniques to reduce the biofouling problem.

In our view, an additional alternative to control biofouling development is the duplication of lantern nets exchanged by half the time during the final culture stage (i.e., 6 months). This means replacing the lantern net in the middle of the final stage of cultivation (i.e., 1.5 months). This proposal can drastically interrupt the development of biofouling before its negative effect becomes significant. Afterward, a new colonization process will start on the cleaned lantern nets, and at the same time, better conditions for water flow will be possible. Likewise, the dispersion of feces, pseudofeces, and metabolites generated inside the lantern net is improved, and finally, there is less competition for seston. Additionally, the reduction of biofouling on the lantern nets will reduce the contribution of organic matter during routine activities or bad practices.

In Samanco Bay, the cultivation of *A. purpuratus* began in the 1990s; however, given the described problems caused by biofouling, no information warns about the economic losses to investment and impacts to this bay. Therefore, measures that help reduce the negative impacts of the cultivation of *A. purpuratus* are urgently needed. In this context, the aim of this study was to investigate whether doubling the lantern net exchange frequency in the final phase of culture reduces biofouling and, in turn, improves the growth and survival of *A. purpuratus*. Our work presents an analysis of the biofouling composition under traditional cultivation and with duplication of lantern nets exchange, growth index measurements, and an economic analysis demonstrating the benefits of implementing this methodology.

2 | METHODS

2.1 | Cultivation area

The study was conducted in the concession of the company Cultivos Marinos Argoper SAC between June and September 2014. This company is dedicated to industrial cultivation of *A. purpuratus* in floating systems and is located in Samanco Bay (9°12' South to 78°32' West), Casma city, Peru.

2.2 | Initial cultivation

Four lantern nets of 10 floors, 2 m in height, 0.5 m in diameter, 21-mm mesh opening, made of monofilament yarn, were used. Each floor refers to a single tier or compartment within the lantern net, where a group of organisms is held separately. The treatments (T), with two replications (L1 and L2), were as follows: T1 = cultivation with lantern net exchanges and T2 = conventional cultivation in the final stage (Figure S1). The lantern nets were placed sequentially within the same culture line, first T1 and then T2. Cultivation began on 13 June at a density of 25 organisms per floor (org floor^{-1}), which were of uniform size and similar weight (81.9 ± 18.2 g). Before culture, epibionts in *A. purpuratus* were removed using spatulas, and 10 organisms per lantern net were randomly taken from both treatments, which were transferred in bags (dry transport) to the Aquatic Biology Laboratory at Universidad Nacional del Santa. Transportation lasted 30 minutes. Here, we recorded shell height using a vernier caliper graduated in millimeters. After recording shell height, the adductor muscle was carefully detached from the valves using a spatula, allowing for the complete removal of the soft tissues. These were then separated into three distinct components: adductor muscle, gonads, and visceral mass. Each tissue component was weighed individually to obtain precise biometric data. Measurements were done using an electric balance (± 0.1 g precision). Later, lantern nets were randomly placed in one of the culture lines (9°12'05.6" South and 78°32'44.2" West) at 6 m depth.

2.3 | Lantern exchange and harvesting

After 30 days, only T1 lantern nets were replaced. For this, the two lantern nets of this treatment were removed using a pulley crane and carefully placed in a boat to avoid the stress of the organisms. Then, we proceeded to remove the culture organisms to clean the lantern nets. Immediately, they were returned to the same lantern nets to continue with the culture. This process was conducted by the researchers and operators with experience in the management of the culture. It is important to note that in this study, "replacement" refers to the retrieval, cleaning, and re-deployment of the same lantern nets in their original location, not the use of new ones. After 96 days, the trial was completed by describing the dominant species on the external and internal surfaces of the lantern nets (for T1 and T2) and estimating the percentage of coverage. The dominant biofouling species were visually identified based on morphological features by experienced researchers in the field. When necessary, a stereomicroscope was used for proper visualization. The dominant biofouling species were registered, and the coverage was calculated using a 10×10 cm metal square in both treatments. *A. purpuratus* organisms were removed by hand from each lantern net, counting the live and dead ones. An organism was classified as dead when it showed no response to tactile stimulation and had an open shell with no resistance upon handling. Then, two organisms were randomly selected from each of the 10 floors of each lantern net (20 per lantern net), resulting in a total of 40 individuals (20 from T1 and 20 from T2), which were placed in bags and transferred to the laboratory for biometric measurements, as described above. For biofouling evaluation, the first, fifth, and tenth floors of each lantern net (representing the top, middle, and bottom positions) from replicates of treatments T1 and T2 were sectioned, placed in bags, and transferred to the laboratory.

2.4 | Sample analysis

In the laboratory, each scallop was gently opened using a scalpel and forceps. Soft tissues were carefully separated from the shell to measure total weight, shell height, and tissue weight. Gonads and adductor muscles were then dissected for the corresponding analysis. From the sectioned apartments, fresh *Ciona intestinalis* organisms were extracted for counting, weighing, and sizing (200 per lantern net). Identification of *C. intestinalis* was based on external morphological characteristics following Brunetti et al. (2015). The other organisms were placed in containers containing 10% formalin and then separated by species, counted, sized, and weighed using a ruler graduated in millimeter and an electric balance of ± 0.1 g. The total number and weight per species and lantern net were obtained by averaging the values found on the three floors and multiplying by 10 (the number of lantern net floors). For the taxonomic identification of the biofouling species, we used taxonomic keys based on the morphological characteristics of each species (Alamo & Valdivieso Milla, 1987; Aldea & Valdovinos, 2005; Baeza-Rojano & Guerra-García, 2013; Banse & Hobson, 1974; Bishop et al., 2023; Guzmán et al., 1998; Ortiz, 2021; Rathbun, 1910; Ryland et al., 2011; Sato-Okoshi et al., 2023; Uribe Alzamora et al., 2013; Zúñiga, 2002), for which a microscope-stereoscope was frequently used.

2.5 | Growth rates and indexes

To standardize the shell height and weight data of *A. purpuratus*, the following equations were used:

1. Absolute growth (AG) (Busacker et al., 1990):

$$AG = V_2 - V_1, \quad (1)$$

where V_1 represents the initial measurement of the adductor muscle weight, gonad weight, or shell height at the beginning of the culture period and V_2 represents the same measurement at the end of the culture period.

2. Absolute growth rate (AGR) (Busacker et al., 1990; Cisneros et al., 2008):

$$AGR = \frac{V_2 - V_1}{t_2 - t_1}, \quad (2)$$

where t_1 is the initial time and t_2 is the final time of the culture period, expressed in days.

3. Relative growth (RG) (Busacker et al., 1990):

$$RG = \frac{V_2 - V_1}{V_1} \times 100, \quad (3)$$

4. Relative instantaneous growth rate (RIGR) (Cisneros et al., 2008; Ricker, 1979):

$$RIGR = \frac{\ln(V_2) - \ln(V_1)}{t} \times 100, \quad (4)$$

where t is the elapsed time between the two measurements, expressed in days.

5. The Gonadosomatic Index (GSI) (Avendaño et al., 2008):

$$GSI = \frac{\text{Gonad weight (g)}}{\text{Total weight of soft parts (g)}} \times 100. \quad (5)$$

6. Condition Factor or Fulton Condition Factor (FC) (Cisneros et al., 2008; Froese, 2006):

$$FC = \frac{\text{Total wet weight of the organism (without valva) (g)}}{\text{valves height (cm)}} \times 100. \quad (6)$$

7. Commercial Yield index for adductor muscle and gonad (CY_{am-g}) (Cáceres-Martínez et al., 1990):

$$CY_{am-g} = \frac{\text{adductor muscle weight (g)} + \text{gonad weight (g)}}{\text{total fresh weight of the organism (g)}} \times 100 \quad (7)$$

8. Commercial Yield index for adductor muscle (CY_{am}) (Cáceres-Martínez et al., 1990):

$$CY_{am} = \frac{\text{adductor muscle weight (g)}}{\text{total fresh weight of the organism (g)}} \times 100. \quad (8)$$

2.6 | Physicochemical parameters

Two days after starting the experiment and one day before harvest at 18:00, 00:00, 06:00, and 12:00 hours, air temperature and wind speed were recorded. A scuba diver took water samples from inside the fifth floor of each lantern net and 5 m outside the lantern nets (OL), recording temperature ($^{\circ}\text{C}$), dissolved oxygen (mg L^{-1}), and total suspended solids (TSS). A thermometer, anemometer $\pm 0.01 \text{ m s}^{-1}$, OATKON oximeter $\pm 0.01 \text{ mg L}^{-1}$, and EC 300 conductivity meter were used. At a fixed station and a depth of 6 m, the company recorded daily the temperature, dissolved oxygen, and salinity of the water, using a YSI 556 multiparameter. Three measurements of these parameters were made, and averages were obtained.

2.7 | Production and costs

To standardize the production of gonads and adductor muscle according to commercial criteria, the results were extrapolated to 1 ha of cultivation (3 lines and 100 lantern nets per line), and based on historical information on export prices and the quality of the product code for exportation, the gross income represented by each treatment was estimated. In parallel to this, the costs of duplication of lantern nets exchange in 1 ha were calculated based on the information provided by three companies that industrially produce *A. purpuratus* in the country, and then the average costs were estimated.

2.8 | Statistical processing

The normality of the data for shell height, total weight, biofouling weight, GSI, FC, CYI, and survival was tested with the Shapiro-Wilk test (Shapiro & Wilk, 1965) ($n < 50$) and the homogeneity of variance with the Brown-Forsythe test (Brown & Forsythe, 1974). To compare means between shell height and total weight between treatments during cultivation, Student's *t*-test was performed ($p < 0.05$). To establish differences between treatments related to biofouling weight, shell height, and weight (gonads and adductor muscle); GSI, FC, and CYI for adductor muscle/gonad and adductor muscle/total fresh weight of the organism; and survival, one-way ANOVA ($p < 0.05$) was performed (Scheffler, 1981). All assumptions for ANOVA were met.

3 | RESULTS

3.1 | Lantern net coverage by biofouling

After 30 days, T1 lantern nets were replaced, and it was observed that 100% of the external and internal surface had abundant biofilm, with sporadic colonies of *C. intestinalis*, *Bugula neritina*, balanids, *Ulva* spp., and *Caprella verrucosa*. Several specimens of the “spider crab” *Stenorhynchus debilis* were also found, and some individuals of two ascidian species could not be identified.

After 96 days, lantern nets of T1 were 100% colonized externally very densely by *Tubularia* sp. and in lower abundance by *B. neritina* and *C. intestinalis* (Figure 1a). At T2 (conventional culture), lantern nets were 100% colonized externally and in high density by *C. intestinalis* and *Austromegabalanus psittacus* (Figure 1b). Internal and external colonization of the lantern nets in T1 was dominated by *C. intestinalis*, which were of medium size with low apparent density. In T2, the dominant species was also *C. intestinalis*, with large sizes hanging in clusters from the top of each floor, forming a dense curtain. Furthermore, we observed the detachment of biofouling in other lanterns (Figure 1c), which was done deliberately prior to the removal of the organisms from the culture (Figure 1d), leading to their disposal in the same cultivation area (Figure 1e).

3.2 | Biofouling on lantern net quantification

Table 1 shows the quantified species as well as the averages of the number of organisms, length, weight per species, and trophic category for both treatments: T1 (lantern net exchange) and T2 (conventional culture). A total of 48 species were recorded across both treatments, with slight differences between them: 37 species in T1 (with 6 exclusive species) and 40 species in T2 (including 11 exclusive species). In addition, Figure 2 shows the importance of biofouling in terms of biomass by taxonomic groups and per lantern net. Here, it can be noticed that chordates and crustaceans were the dominant groups at T1, but they did not exceed 20 kg per lantern net; however, chordates add up to more than 60 kg per lantern net at T2 and crustaceans about 40 kg per lantern net. Due to the effect of lantern net exchange, the biomass was at T1 = 47.59 and at T2 = 131.87 kg per lantern net, which means that the biomass is reduced by 2.77 times due to the effect of lantern net exchange. If these data are extrapolated to 1 ha of *A. purpuratus* culture (1 ha = 3 lines and 1 line = 100 lantern nets), 14.28 t ha⁻¹ of biofouling would be produced with the lantern net exchange approach and 39.56 t ha⁻¹ with the conventional practice.

In terms of species abundance, there is a clear dominance in the treatments. In T1, *C. intestinalis* accounts for 39.52% (Figure 3a), while in T2, more than 50% is represented by *C. intestinalis* and almost 30% by *A. psittacus* (Figure 3b). Additionally, biofouling species were recorded in 11 different trophic categories (producer, predator, filter, herbivore, detritivore, predator-omnivore, herbivore-commensal, predator-necrophagous, commensal, predator-scavenger, or parasite), with filter feeders being the most significant group. The biomass of filter feeders in T2 was 9.5 times higher than that in T1 (Figure 4).

3.3 | Effect of biofouling on *A. purpuratus*

At the start of the experiment and at the end (harvesting), the gonads appeared brightly colored, shiny, turgid (characteristic of the species), and free of parasites. Similarly, the adductor muscle was shiny and had a firm consistency. No statistically significant differences ($p < 0.05$) were determined in shell height, gonad weight, or adductor muscle weight between treatments (T1 and T2) at the beginning of the culture. However, at the time of harvest, the average values of these same parameters were significantly higher in T1 than in T2 ($p < 0.05$) (Table 2).

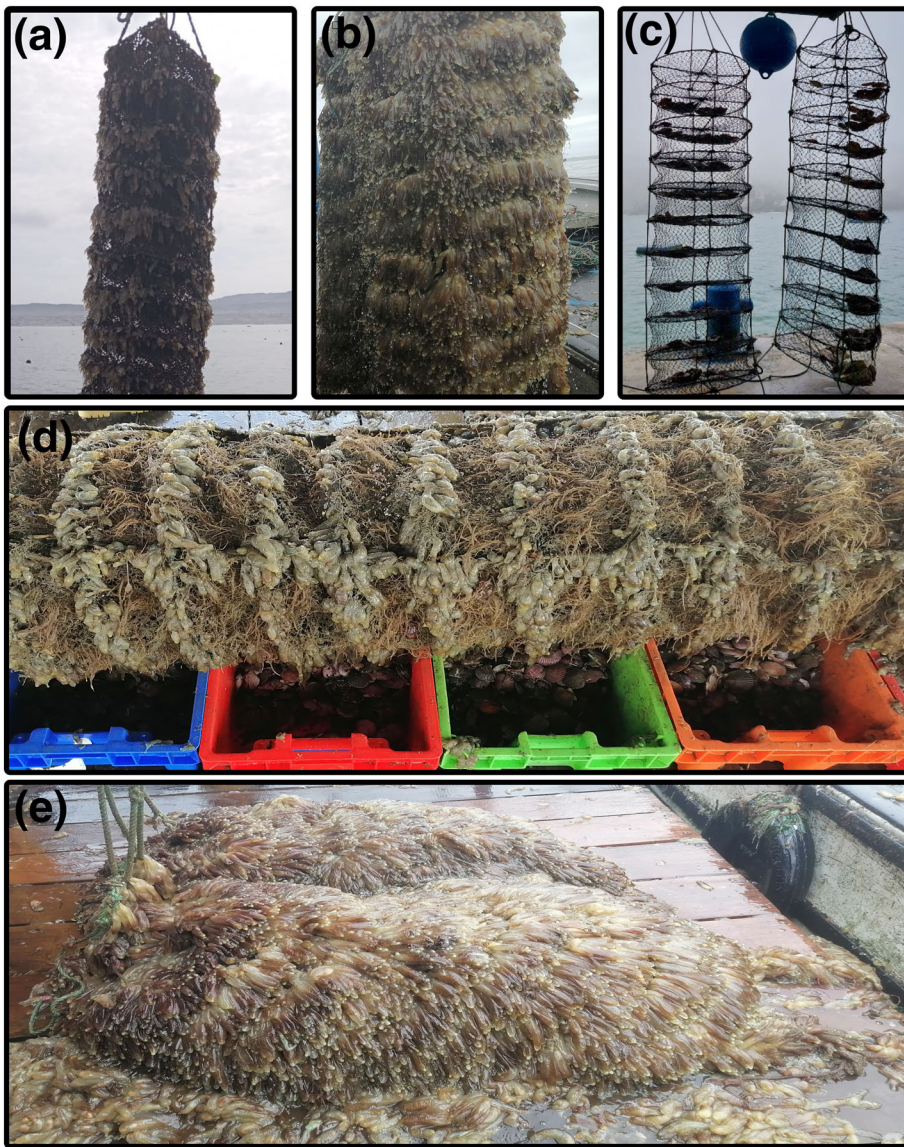


FIGURE 1 Dominant biofouling organisms at the time of harvest. (a) Lantern net from Treatment 1 (T1), showing less biofouling. (b) Lantern net from Treatment 2 (T2), heavily colonized by *Ciona intestinalis*. (c) Clean lantern net of *A. purpuratus* with no biofouling. (d) Harvesting of *A. purpuratus* into cuvettes. (e) Full view of a culture lantern net colonized predominantly by *C. intestinalis*.

3.4 | Growth rates for shell height and weight

Growth rates for shell height and gonad weight were significantly higher in organisms from T1 than those from T2 (Table 3). For instance, AGR of gonad in T1 was 39.6% higher than that in T2 (Table 3). No statistically significant differences were found between treatments T1 and T2 in adductor muscle weight at harvest ($p > 0.05$), indicating similar growth of this parameter under both culture conditions.

TABLE 1 Epibionts identified in the culture lantern nets of *A. purpuratus* in Samanco Bay, Peru.

Taxonomic group	TC	T1			T2		
		Number	Size (cm)	Weight (g)	Number	Size (cm)	Weight (g)
Chlorophyta							
<i>Caulerpa filiformis</i> (Suhr) Hering, 1841	P	—	—	—	—	2.50 ± 0.4	13.0
<i>Enteromorpha</i> sp.	P	—	0.5 ± 0.2	0.8	—	1.50 ± 0.3	5.0
<i>Ulva lactuca</i> (Linnaeus, 1753)	P	—	1.91 ± 0.2	9.5	—	2.20 ± 0.1	2.5
Phaeophyta							
<i>Giffordia</i> sp.	P	—	1.90 ± 0.2	9.5	—	2.20 ± 0.1	2.5
Rhodophyta							
<i>Rhodymenia howeana</i> (E. Dawson, 1941)	P	—	—	—	—	2.4 ± 0.0	1.0
Cnidaria							
<i>Actinaria</i> sp.	Pr	20	2.10 ± 0.2	3.7	—	—	—
<i>Actinostola</i> sp.	Pr	1409	0.81 ± 0.3	151.9	1915	0.70 ± 0.2	406.0
<i>Renilla koellikeri</i> (Pfeffer, 1886)	F	10	4.20 ± 1.2	28.3	—	—	—
<i>Tubularia</i> sp.	F	451142	2.65 ± 0.6	3385.7	525733	3.71 ± 1.1	3943.0
Brachiopoda							
<i>Discinisca lamellosa</i> (Broderip, 1833)	F	13	1.52 ± 0.2	4.0	30	1.60±	9.0
Bryozoa							
<i>Bugula flavellata</i> (Thompson in Gray, 1848)	F	15234	1.96 ± 0.3	443.6	515	1.5 ± 0.5	15.0
<i>Bugula neritina</i> (Linnaeus, 1758)	F	23670	3.04 ± 0.6	4548.1	742	3.30 ± 0.7	142.5
<i>Membranipora membranacea</i> (Linnaeus, 1767)	F	4	—	—	3	—	2.5
Chordata							
<i>Botrylloides violaceus</i> (Oka, 1927)	F	2	—	53.4	2	—	99.5
<i>Botrylloides perspicuous</i> (Herdman, 1886)	F	2	—	27.9	3	—	53.5
<i>Calamus brachysomus</i> (Lockington, 1880)	Pr	10	6.41 ± 0.5	25.3	—	—	—
<i>Ciona intestinalis</i> (Linnaeus, 1767)	F	7020	7.22 ± 0.5	18808.2	10125	13.18 ± 4.4	67032.9
Crustacea							
<i>Ampelisca gibba</i> (G.O. Sars, 1882)	H	1258996	—	6712.5	167885	—	203.9
<i>Austromegabalanus psittacus</i> (Molina, 1788)	F	24541	2.73 ± 1.3	7031.0	6520	2.92 ± 1.5	38238.6

(Continues)

TABLE 1 (Continued)

Taxonomic group	TC	T1			T2		
		Number	Size (cm)	Weight (g)	Number	Size (cm)	Weight (g)
<i>Balanus laevis</i> (Bruguière, 1789)	F	77	0.50 ± 0.1	4.7	290	0.50 ± 0.1	11.0
<i>Caprella verrucosa</i> (Boeck, 1871)	D	1740641	1.3 ± 0.4	2495.2	273840	1.3 ± 0.4	332.7
<i>Erichthonius</i> sp.	F	145298	—	175.6	19275	—	23.4
<i>Eurypanopeus crenatus</i> (Milne Edwards, 1834)	Pr	—	—	—	15	2.20 ± 0.0	17.0
<i>Eriphia squamata</i> (Stimpson, 1859)	Pr	7	2.30 ± 0.2	10.7	15	2.1 ± 0.2	22.0
<i>Pilumnus</i> sp.	Pr	27	2.00 ± 0.3	21.7	20	1.70 ± 0.1	13.0
<i>Pilumnoides perlatus</i> (Poepig, 1836)	Pr	37	2.18 ± 0.1	66.7	80	2.30 ± 0.1	96.5
<i>Pugettia</i> sp.	H	10	1.50 ± 0.1	3.0	—	—	—
Hemichordata							
<i>Enteropneusta</i> sp. (Gegenbaur, 1870)	F	7	12.20 ± 1.3	15.9	—	—	—
Equinodermata							
<i>Arbacia spatuligera</i> (Valenciennes, 1846)	Pr-O	20	1.94 ± 0.1	20.7	25	1.78 ± 0.1	30.0
<i>Caenocentrotus gibbosus</i> (L. Agassiz, 1846)	H	—	—	—	15	1.40 ± 0.3	9.5
<i>Ophiactis</i> sp.	D	—	—	—	20	1.20 ± 0.1	0.5
Mollusca							
<i>Argopecten purpuratus</i> (Lamarck, 1819)	F	366	1.40 ± 0.5	152.0	35	1.54 ± 0.6	31.5
<i>Barbatia barbata</i> (Broderip & Sowerby, 1829)	F	216	0.70 ± 0.2	59.2	185	1.43 ± 0.6	41.5
<i>Crepidula dilatata</i> (Lamarck, 1822)	H-Co	—	—	—	15	1.02 ± 0.3	3.0
<i>Crucibulum spinosum</i> (G.B. Sowerby, 1824)	—	—	—	25	0.8 ± 0.1	31.5	—
<i>Hiatella solida</i> (Sowerby, 1834)	F	44	1.20 ± 0.3	18.2	45	2.00 ± 0.2	24.5
<i>Pteria sterna</i> (Gould, 1851)	F	1	7.40 ± 0.8	6.9	25	2.16 ± 1.0	68.0
<i>Semimytilus algosus</i> (Gould, 1850)	F	3480	1.45 ± 0.6	1244.9	2725	2.23 ± 1.2	18565.0
<i>Sphenia fragilis</i> (Adams & Adams, 1854)	F	40	1.40 ± 0.2	10.2	20	1.5 ± 0.3	7.0
Platyhelminthes							
<i>Notoplana queruca</i> (Marcus & Marcus, 1968)	Pr	17	2.20 ± 0.3	12.5	—	—	—

TABLE 1 (Continued)

Taxonomic group	TC	T1			T2		
		Number	Size (cm)	Weight (g)	Number	Size (cm)	Weight (g)
<i>Planaria</i> sp.	Pr-Ne	20	1.34 ± 0.2	4.0	—	—	—
Polychatea							
<i>Halosydna brevisetosa</i> (Kinberg, 1856)	Co	43	2.97 ± 0.4	6.9	350	2.56 ± 0.4	85.5
<i>Halosydna johnsoni</i> (Darboux, 1899)	Co	—	—	—	30	1.85 ± 0.5	0.5
<i>Hydroides</i> sp.	F	176	1.86 ± 0.5	0.7	145	1.75 ± 0.4	1.0
<i>Lumbinereis</i> sp.	Pr-S	—	—	—	10	6.25 ± 0.2	3.0
<i>Neanthes succinea</i> (Leuckart, 1847)	D	—	—	—	105	3.50 ± 1.4	4.5
<i>Nereis calaona</i> (Grube, 1857)	Pr	3866	4.17 ± 0.8	1933.1	11135	4.22 ± 0.7	2283.7
<i>Polydora</i> sp.	Pa	—	—	—	115	2.20 ± 0.5	0.5
Other							
Fish egg	—	—	—	77.6	—	—	—
Total species	—	—	37	—	—	40	—
Total (kg lantern net ⁻¹)	—	—	47.59	—	—	131.87	—
Total (t ha ⁻¹)	—	—	14.28	—	—	39.56	—

Note: The Trophic Category (TC), number, size, weight of individuals and by species, and weight per lantern net and per hectare of biofouling, according to treatments, are presented.

Abbreviations: Co, commensal; D, detritivore; F, filter-feeder; H, herbivore; Ne, necrophage; P, producer; Pa, parasite; Pr, predator; S, scavenger.

3.5 | Indexes

The Gonadosomatic Index (GSI) data indicate that between the beginning and end of the culture, there was an increase of 7.95% in T1 and 7.05% in T2 (Figure 5a), with a statistically significant difference ($F_c = 126.6785$, $F_{(1,91;0.05)} = 3.95$). The Condition Factor (CF) decreased gradually (Figure 5b), with a slightly greater decline in T1 (−4.62) than in T2 (−4.40), also statistically significant ($F_c = 91.5494$, $F_{(1,91;0.05)} = 3.95$). The Commercial Yield Index for gonad (CYI_{am-g}) was better in T1 (20.35%) than in T2 (16.42%) (Figure 5c). Additionally, the CYI_{am} value in T1 (11.7%) was higher than that in T2 (9.37%), with both comparisons showing significant differences ($p < 0.05$) (Figure 5d). As shown in Figure 5, the values for all indexes (GSI, CF, CYI_{am-g} , and CYI_{am}) in treatment T1 were higher than those in treatment T2.

3.6 | Survival

Survival rates at the end of the experiment revealed a statistically significant difference between treatments ($F_c = 112.15$, $F_{(2,3);0.001} = 8.33$). The mean survival in T1 was 97.4%, while in T2, it was 86.6% (Table 4). At the beginning of the culture, each lantern net contained 250 organisms. At harvest, the number of surviving individuals per lantern ranged from 241 to 246 in T1 (corresponding to survival rates of 96.4% and 98.4%) and from 216 to 217 in T2 (survival rates of 86.4% and 86.8%).

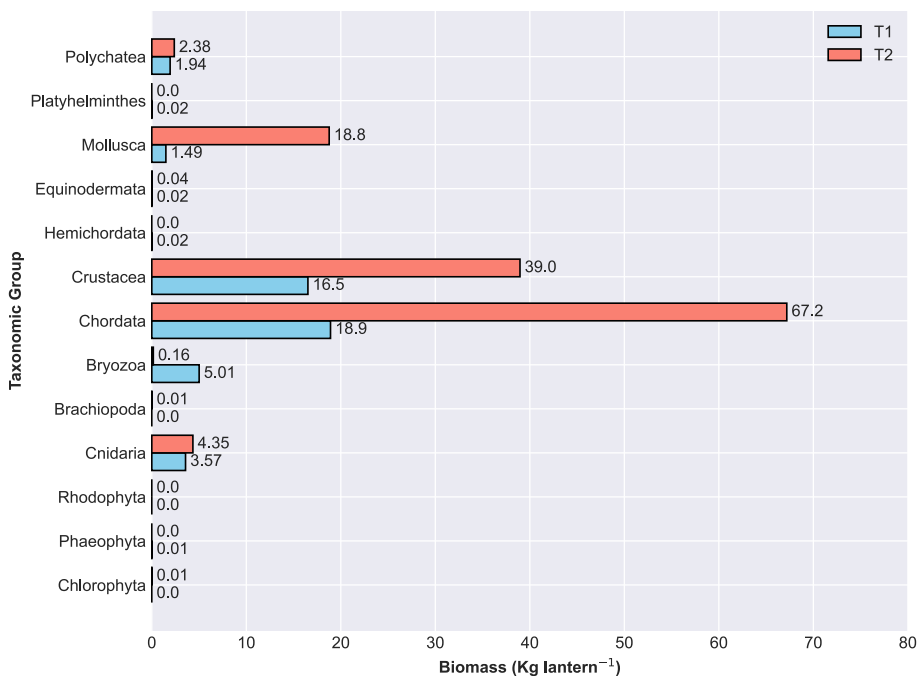


FIGURE 2 Biomass by taxonomic groups of biofouling organisms developed on *A. purpuratus* suspended culture lantern nets in Samanco Bay, categorized by treatment. Light blue bars correspond to T1 (lantern net exchange) and light red bars to T2 (conventional culture).

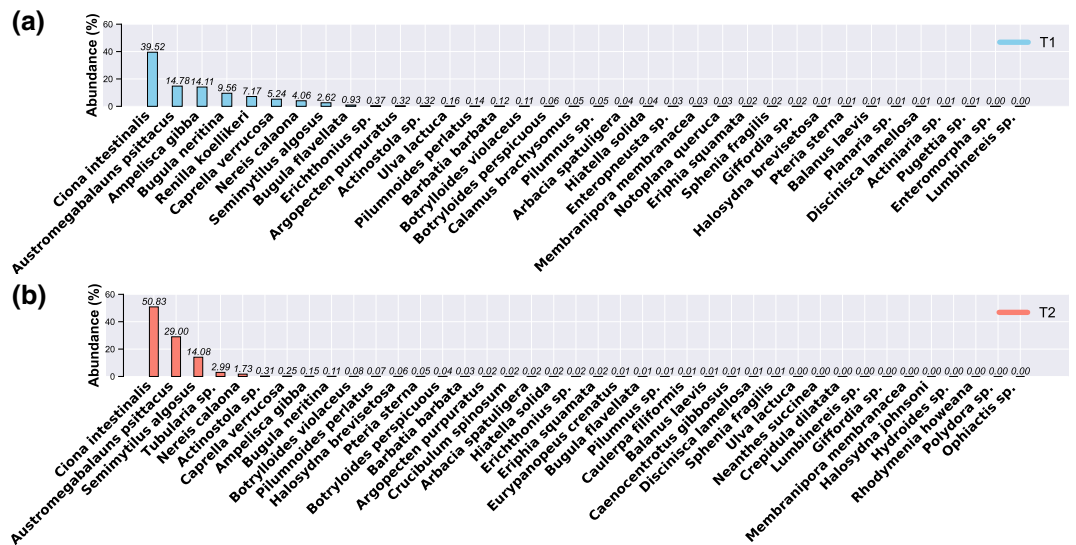


FIGURE 3 Relative biomass abundance of biofouling species on *A. purpuratus* culture lantern nets in Samanco Bay, shown for (a) T1 and (b) T2.

3.7 | Abiotic factors

Initially, cultivation proceeded under normal weather conditions; however, the final 30 days, including the harvest period, were marked by strong winds and significant wave activity (Table 5). Wind speeds at the start of

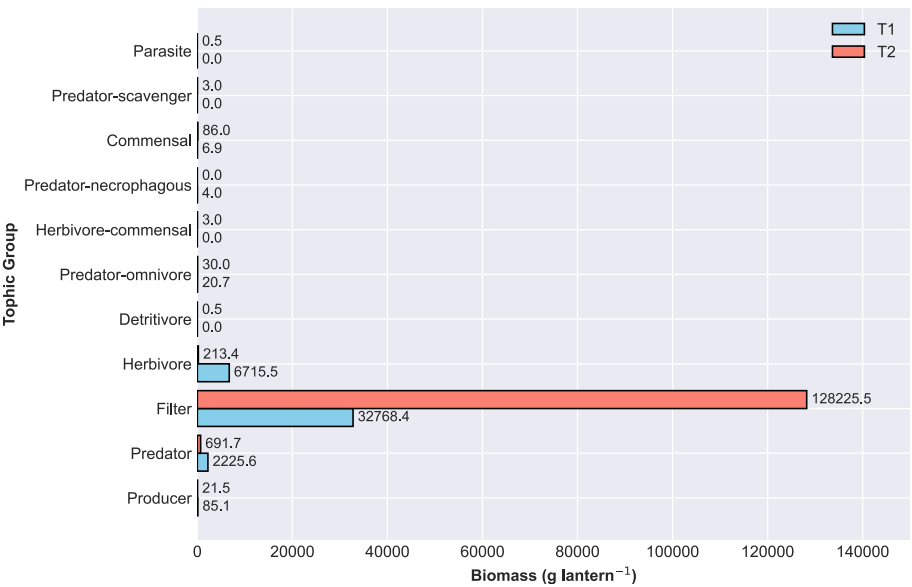


FIGURE 4 Biofouling biomass categorized by trophic group (feeding behavior) developed on lantern nets in the suspended culture of *A. purpuratus* in Samanco Bay (Ancash, Peru), grouped by treatment. Light blue bars correspond to T1 (lantern net exchange) and light red bars to T2 (conventional culture).

TABLE 2 Comparison of mean shell height (VH), gonad weight (GW), and adductor muscle weight (AMW) at the beginning and at harvest for *A. purpuratus* cultivated under treatments T1 and T2, each with two lantern net replicates (L1 and L2).

Treatments	Lanterns	Beginning of the culture				Harvest			
		<i>n</i>	VH (mm)	GW (g)	AMW (g)	<i>n</i>	VH (mm)	GW (g)	AMW (g)
T1	L1	10	77.44 ± 5.11	7.06 ± 1.32	8.36 ± 2.00	23	91.00 ± 7.06	11.97 ± 3.15	14.82 ± 3.43
	L2	10	80.10 ± 3.28	9.19 ± 3.91	11.82 ± 2.46	21	89.81 ± 6.00	12.89 ± 3.87	18.11 ± 4.87
	Average	—	78.77 ± 4.39	8.13 ± 3.04	10.09 ± 2.81	—	90.41 ± 0.84	12.43 ± 0.65	16.39 ± 4.45
	L1	10	79.00 ± 4.92	7.16 ± 2.34	9.55 ± 1.99	23	86.87 ± 7.20	10.70 ± 3.53	14.61 ± 3.51
T2	L2	10	84.10 ± 5.28	7.03 ± 2.68	13.51 ± 1.56	26	91.19 ± 4.95	8.83 ± 2.83	14.14 ± 2.72
	Average	—	81.55 ± 5.61	7.10 ± 2.45	11.53 ± 2.67	—	89.03 ± 3.05	9.70 ± 3.28	14.36 ± 3.09
Comparison (T1 vs. T2)		—	<i>t</i> = 0.967, ns	<i>t</i> = 0.965, ns	<i>t</i> = 1.110, ns	—	<i>t</i> = 0.6* <i>t</i> = 0.26*	<i>t</i> = 0.26*	<i>t</i> = 1.13*

Abbreviations: AMW, adductor muscle weight; GW, gonad weight, *n*, number; VH, shell height.
Note: *Significance = 0.05.

the cultivation ranged from 1.65 ± 0.47 to $4.54 \pm 1.16 \text{ m s}^{-1}$, whereas during the harvest period, wind speeds increased from 4.17 ± 0.67 to $6.98 \pm 1.23 \text{ m s}^{-1}$, accompanied by waves reaching approximately 1.5 meters in height.

TABLE 3 Absolute growth (AG), absolute growth rate (AGR), relative growth (RG), and relative instantaneous growth rate (RIGR) of *A. purpuratus* in culture treatments T1 and T2.

Parameter	Rate	Treatments	
		T1	T2
Shell height (mm)	Beginning	72.77 ± 4.39	81.55 ± 5.61
	Harvest	90.43 ± 0.84 ^a	89.16 ± 3.05 ^b
	AG (mm)	17.66	7.16
	AGR (mm month ⁻¹)	5.50	2.38
	RG (%)	24.27	8.78
	RIGR (mm.day ⁻¹)	0.22	0.09
Gonad weight (g)	Beginning	8.13 ± 3.04	7.10 ± 2.45
	Harvest	12.41 ± 0.65 ^a	9.70 ± 3.28 ^b
	AG (g)	4.28	2.60
	AGR (g month ⁻¹)	1.34	0.81
	RG (%)	52.64	36.62
	RIGR (g day ⁻¹)	0.44	0.38
Adductor muscle weight (g)	Beginning	10.09 ± 2.81	11.53 ± 2.67
	Harvest	16.39 ± 4.45 ^a	14.36 ± 3.09 ^a
	AG (g)	6.30	2.83
	AGR (g month ⁻¹)	1.97	0.88
	RG (%)	38.44	24.54
	RIGR (g day ⁻¹)	0.5054	0.2286

Note: Different letters indicate statistical difference at a level of $p < 0.05$.

The environmental conditions within the bay during the study were influenced by an initial rise in surface water temperature during the first month, which was above normal due to a slight warming effect that later dissipated. Throughout the entire study period, dissolved oxygen levels remained above 5 mg L⁻¹, while salinity was recorded at 34.79 ± 0.88 ups (Supplementary Figure 2). Regarding the measurements of temperature, oxygen, and total suspended solids (TSS) between 18:00 and 12:00 hours, no significant differences were detected inside and outside the lantern nets at either the beginning or end. Water temperatures ranged from 20.3 to 22.5°C, dissolved oxygen levels between 6.7 and 9.3 mg L⁻¹, and TSS between 18.4 and 20.6 g L⁻¹ during both stages of cultivation, including the initiation (Figure 6a) and harvesting of T1 and T2 (Figure 6b,c, respectively).

3.8 | Economic aspects

The use of lantern net exchange in T1 generated a gross income that was 25.6% higher than in T2 (Table 6). This result was based on several factors: (a) weight of gonad and adductor muscle (Table 2), (b) survival rates recorded in each treatment (Table 4), (c) production extrapolated to 1 hectare, and (d) a cost per kilogram of product derived from the average data. The pricing was based on exportation standards for *A. purpuratus* products, specifically the “Roe on” presentation, which includes both gonads and adductor muscles, categorized by size (caliber codes 8–12, 10–20, and 30–40 pieces per pound). Additional operating costs related to lantern net exchange in T1 are detailed in Table 7, calculated as the arithmetic average from the company conducting the study, along with data from two other companies.

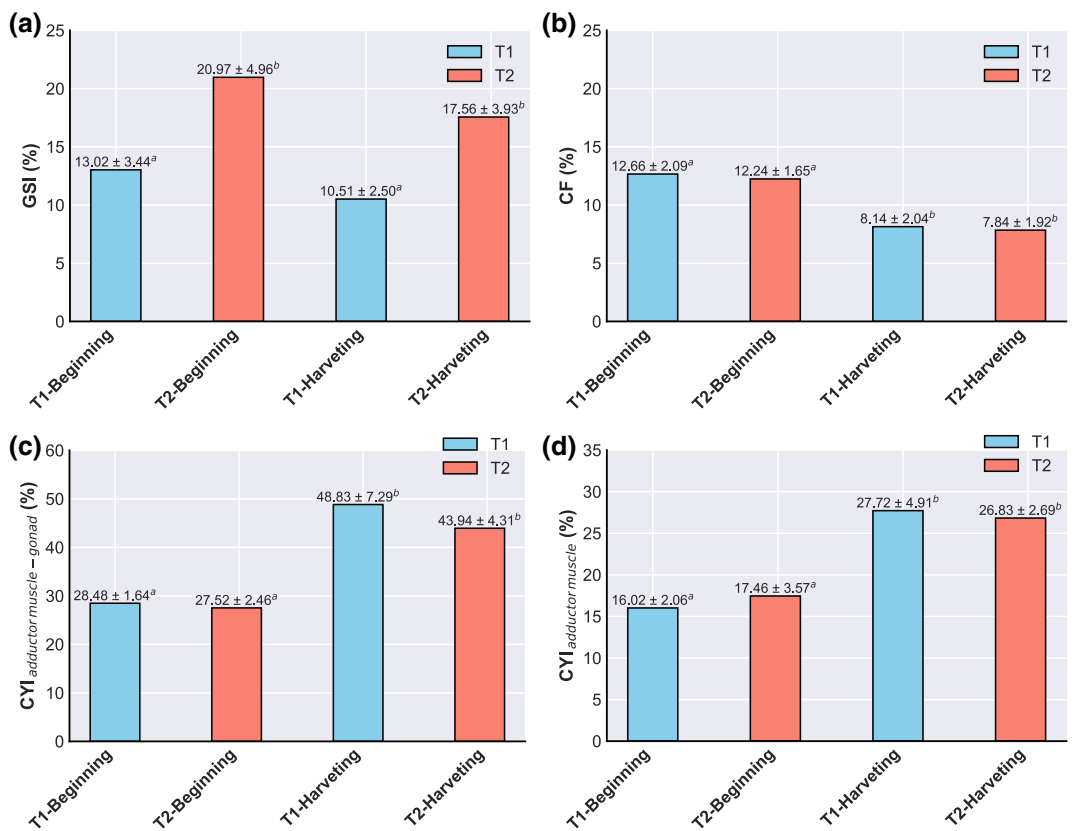


FIGURE 5 (a) Variation in Gonadosomatic Index (GSI), (b) Condition Factor (CF), (c) Commercial Yield Index for adductor muscle-gonad (CYI_{am-g}), and (d) adductor muscle (CYI_{am}) by treatment groups T1 and T2, illustrating the effects of lantern net exchange in *A. purpuratus* culture in Samanco Bay.

TABLE 4 Survival of *A. purpuratus* in suspended culture in Samanco Bay, categorized by treatment.

Recording	T1		T2	
	L1	L2	L1	L2
Beginning of culture (organisms per lantern net)	250	250	250	250
Average	250 (100%)		250 (100%)	
Harvest (organisms per lantern net)	246 (98.4%)	241 (96.4%)	216 (86.4%)	217 (86.8%)
Average	243.5 (97.4%)		216.5 (86.6%)	

4 | DISCUSSION

4.1 | Biofouling development

The observation that lantern nets in both treatments were 100% covered by biofouling (particularly in T2) is linked to the high primary productivity of Samanco Bay (Guillén & Izaguirre de Rondán, 1968). This productivity supports the settlement and larval development of sessile organisms on hard surfaces and shallow areas, providing food resources for their rapid growth. In this way, the presence of 37 species in T1 and 40 species in T2 (Table 1) reflects

TABLE 5 Wind conditions (Beaufort scale) and sea state (Douglas scale) recorded during the initiation and harvest phases of *A. purpuratus* suspended culture in Samanco Bay.

Scale	Moment	Sampling hours			
		18:00	00:00	06:00	12:00
Beaufort	Initial	4	3	2	2
	Harvest	7	7	4	5
Douglas	Initial	3	2	2	1
	Harvest	6	6	6	4

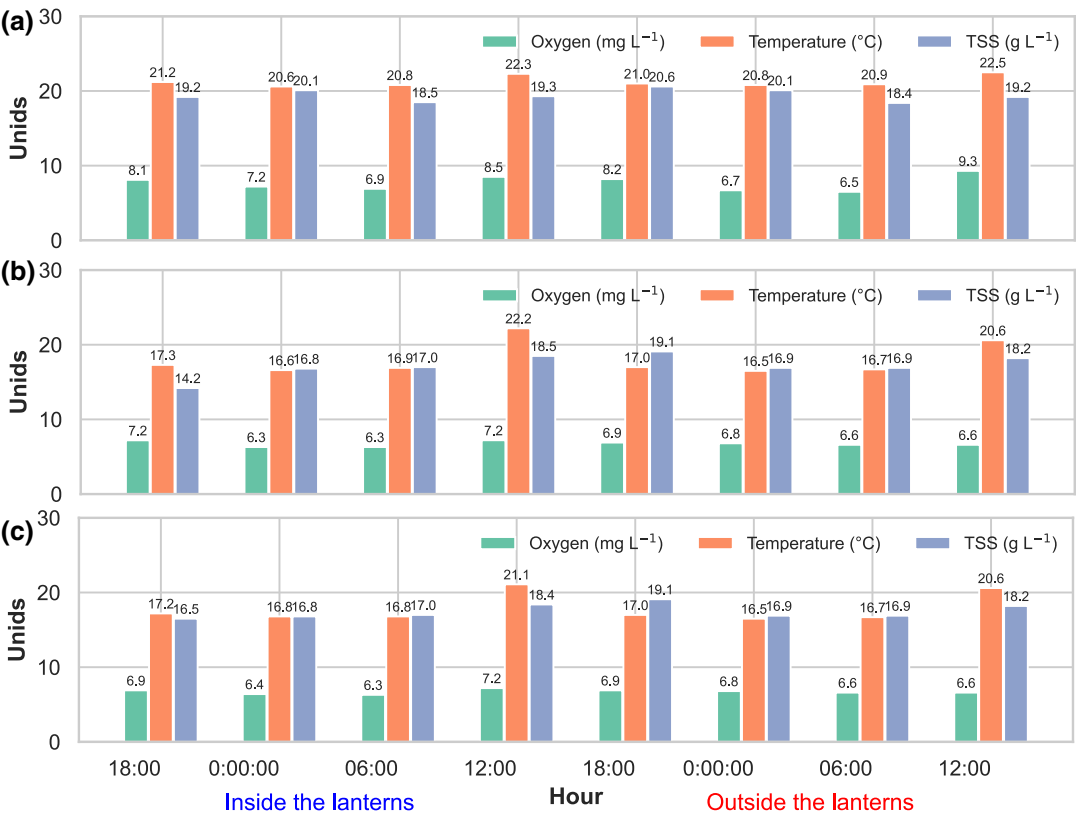


FIGURE 6 Temperature, dissolved oxygen, and TSS measurements. (a) The values at the initiation of culture, (b) the values of T1 at the harvest, and (c) the values of T2 at the harvest, both inside and outside the lantern nets in all cases.

the high biological diversity of Samanco Bay, which is habitat of 111 invertebrate species and 10 macroscopic algae. This diversity also contributes to a rich supply of larvae that settle on the lantern nets (Loayza-Aguilar et al., 2023).

In the same bay, lantern net cultures recorded 15 biofouling species during the El Niño event in 1998 (Pacheco & Garate, 2005), 40 species in 2009 (Loayza & Tresierra, 2014), and 80 species between 2017 and 2019 (Tapia-Ugaz et al., 2022). In Tongoy, Guanaqueros, and Inglesa bays (Chile), where *A. purpuratus* is industrially farmed, 63 biofouling species were reported, with 27 common across winter and summer (Uribe & Blanco, 2001). This variation in biofouling diversity and biomass is influenced by factors such as temperature, species introduction, chemical pollution, eutrophication, phytoplankton blooms, physical habitat alterations, global climate change, and

local conditions, including light levels, photoperiod, primary productivity, currents, sea state, and seasonality (Silva et al., 1980; Steneck & Carlton, 2001). Understanding these factors is crucial for developing effective biofouling control strategies, which can help to mitigate environmental impacts and enhance the profitability and sustainability of the aquaculture industry.

Notwithstanding the high richness of species in the biofouling community, only five species are of greatest importance: *C. intestinalis*, *Austromegabalanus psittacus*, *Tubularia* sp., *Bugula neritina*, and *Semimytilus algosus*, in both treatments (T1 and T2). These species stand out for their size, biomass, and/or number (Table 1), thus exerting a weighted influence on the community assemblage and determining the nature of the interspecific relationships. In this context, *C. intestinalis* contributes according to its number, size, and biomass; *A. psittacus* for its number, size, rigid structure, and biomass; and *B. neritina* and *Tubularia* sp. for their number and size. They can also modulate the habitats or microhabitats for some species, mainly changing the availability of resources for the community, which is the reason they are considered ecosystem engineering species (Jones et al., 1994).

In this sense, it has been argued that *A. psittacus* and *S. algosus*, as engineering species, stand out for acting as habitat formers, providing physical spaces for the development of other species, such as polychaetes, crustaceans, and mollusks (Vázquez et al., 2008; Zagal & Hermosilla, 2007). On the other hand, *B. neritina*, due to its arborescent structure, generates habitat for *Barbatia barbata*, *Hiatella solida*, *Sphenia fragilis*, polychaetes, and mainly *Caprella verrucosa* (Loayza & Tresierra, 2014; Sáenz-Arias et al., 2020) because very high densities of the latter species were found in T1 (6.4 times higher than in T2), in accordance with greater area of attachment due to higher biomass of *B. neritina* (Table 1). *Tubularia* sp. was the most abundant sessile species in both treatments (Table 1), attenuating the circulation of water inside the lantern net and concentrating the seston inside the lantern net, but at the same time favoring the settlement of sessile and mobile species (Caine, 1987), such as *Alia* sp., *H. solida*, *S. fragilis*, *Ampellisca*

TABLE 6 Estimated income from gonad and adductor muscle production in *A. purpuratus* culture using lantern net exchange (T1) and conventional methods (T2).

Parameter	T1	T2
Production		
Gonads (kg ha ⁻¹)	906.56	631.47
Adductor muscle (kg ha ⁻¹)	1197.29	934.84
Gonad + adductor muscle (kg ha ⁻¹)	2103.85	1566.31
Code	Roe on (10–20)	Roe on (10–20)
Price roe on (USD kg ⁻¹)	15	15
Export income (USD ha ⁻¹)	31557.75	23494.65
Difference by income (T1 – T2)	USD 8063.10	

TABLE 7 Operational costs for lantern net replacement in *A. purpuratus* production compared to conventional methods, extrapolated to 1 ha of cultivation (exchange rate: 3.85 PEN/USD).

Activity	Unit cost (PEN)	Cost ha ⁻¹ (PEN)	
		T1	T2
Exchange of lantern nets	14.0	4200.0	–
Washing and repair of lantern nets	5.0	1500.0	–
Lantern nets reflow	2.5	–	750.0
Total (PEN)		5700.0	750.0
Total (USD)		1480.52	194.81

sp., *C. verrucosa*, *Erichthonius* sp., polychaetes, and particularly in close association with *C. intestinalis*, of which it is a frequent epibiont. On the other hand, *S. algosus* generates biogenic substrate, providing shelter for polychaetes and microcrustaceans.

The process of marine biofouling formation, as a community assembly, where cooperative relationships predominate (Hartl et al., 2006), is complex and occurs in four stages: formation of a conditioned film, primary colonization, secondary colonization, and tertiary colonization. The first stage involves the adsorption of dissolved organic molecules (proteins, polysaccharides, and proteoglycans). In the second stage, colonization by prokaryotes and some unicellular eukaryotes (diatoms, flagellates, amoebae, and ciliates) occurs, with the formation of biofilm. In the third, colonization by spores of macroscopic algae and protozoa occurs. In the last phase, it arises the assembly of larvae of larger invertebrate organisms (barnacles, balanids, mussels, polychaetes, and bryozoans) (Cao et al., 2011; Characklis, 1989; Papadopoulos et al., 2023). Considering that cell adhesion and biofilm formation are primary steps for macrofouling, the most promising marine biofouling mitigation approach is to delay and control microfouling events (Characklis, 1989). This was the context for the design of the present investigation, as observed in Figure 7, where T1 interrupts the biofouling development process by retrieving, cleaning, and redeploying the same lantern nets. This process caused the biofouling colonization to return to the initial stage after 30 days (Figure 7b), thus preventing the biomass from reaching its maximum growth.

In the culture of *A. purpuratus* in Tongoy Bay (Chile), a lantern net produces between 80 and 100 kg of biofouling (Uribe et al., 2008; Uribe & Blanco, 2001) and in Samanco Bay between 68.04 and 73.42 kg lantern net⁻¹ (Loayza & Tresierra, 2014). The results in the present work provide evidence that biofouling production in Samanco Bay is increasing as the weight of biofouling in T2 was 131.87 kg lantern net⁻¹ compared to 85.32 kg lantern net⁻¹ in T1 (Table 1). At harvest, the average gonad weight was 12.41 g in T1 and 9.70 g in T2, while adductor muscle weight was 16.39 g in T1 versus 14.36 g in T2 (Table 3). These differences were statistically significant for gonads and showed a consistent biological trend for muscle tissue. When analyzed in terms of growth rates, T1 outperformed T2 in all parameters: gonad absolute growth (4.28 g vs. 2.60 g), relative growth (52.64% vs. 36.62%), and relative instantaneous growth rate (0.44 g day⁻¹ vs. 0.38 g day⁻¹). Similar trends were observed for adductor muscle growth. These differences, while not massive individually, become economically relevant when scaled to commercial aquaculture production. Similar trends have been reported by Fitridge et al. (2012), who described reduced tissue yields in bivalves exposed to heavy biofouling, due to increased competition for food and oxygen, and energy diversion toward stress response mechanisms.

For this reason, the lantern net exchange method represents a significant improvement as it reduces the biomass of biofouling by 63.91% (Table 1) compared to conventional technology, thus generating more favorable conditions for the growth of *A. purpuratus*. The high biofouling production in Samanco Bay could be attributed to the fact that 53% of the species involved are filter feeders (in T1 they represent 75.7% of the biomass and 97.3% in T2; Table 1, Figure 3). Filter feeders can take advantage of the high primary productivity (promoted by upwelling events) and of eutrophication (Loayza et al., 2023). Eutrophication has been evidenced for some years now by the accelerated increase of *Caulerpa filiformis* and *Ulva* spp.

Regarding the development of biofouling inside the lantern nets, the dominant species in the two treatments was *C. intestinalis* (Figure 3). However, the replacement of lantern nets significantly influenced the number and size of these organisms: in T1 it was 7.22 cm, 54.78% lower than in T2 (13.18 cm) (Table 1). Because of the high density of this species in T2 (Table 1) and its size, which hung in clusters from the “ceiling” on each floor (20 cm in height) (Figure 1), it occupied 70% of the lantern net floor volume, which could have caused: (a) greater interference in the water circulation in T2, and with it the flow of seston, oxygen renewal, dispersion of feces, pseudofeces, and metabolites concentration (Freitas et al., 2023); (b) greater competition for seston with *A. purpuratus* (Freitas et al., 2023); and (c) direct contact with the organisms in the culture at times of significant waves, which may have interfered with the mechanical process of keeping the shells open, and with the filtration rate (Fitridge et al., 2012). This could have translated into stress, with repercussions on the growth of organisms in culture (Cao et al., 2011; Núñez et al., 2007), reflected in the Condition Factor (CF) (Figure 5),

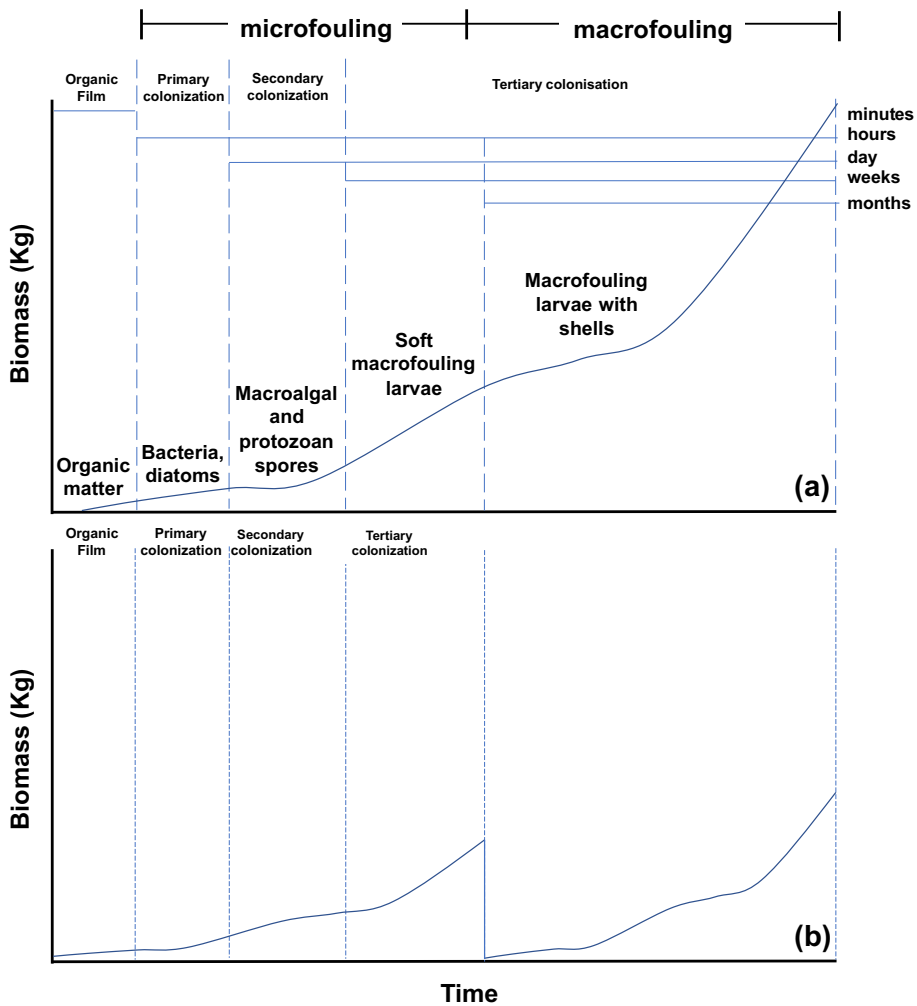


FIGURE 7 Conceptual schematic illustrating the hypothesized biofouling colonization process on lantern nets: (a) conventional cultivation method (T2) and (b) cultivation with lantern net replacement (T1). This shows how lantern net replacement may interrupt biofouling progression during the culture of *A. purpuratus* in Samanco Bay.

when comparing the growth of *A. purpuratus* at T1 and T2. This condition could worsen in two circumstances: (a) in spring and summer, when current velocity and water renewal rate in the lantern nets are lower, and (b) when ascidians eventually develop (Table 1), which clogs the meshes, for now not very important. Ascidians are potentially invasive organisms that develop in calm waters (in summer) and abundant suspended organic matter (Galicia et al., 2018), such as that generated inside the lantern nets due to biofouling.

In the culture of *A. purpuratus* in Chile, *C. intestinalis* can reach 6000 org lantern net⁻¹, with a respiration rate of 0.364 mL O₂ L⁻¹ and a high filtration rate, between 0.997 L h⁻¹ in 1-g organisms (Uribe et al., 2008) and 50–60 mL min⁻¹ (3–3.6 L h⁻¹) per gram of dry weight (Petersen, 2016), and ingestion rate of 0.259 mg h⁻¹ (Uribe et al., 2008). Thus, a large number of organisms can reduce water turbidity and food availability by competing with other species (Cohen et al., 2001). Due to the replacement of lantern nets, this species in T1 was recorded at 7020 org lantern net⁻¹, similar to the above, but 30.7% lower than in T2 (Table 1). Therefore, replacing the nets helps reduce competition for oxygen and food with *A. purpuratus*.

Biofouling on lantern nets, particularly from species such as *A. psittacus*, accelerates material degradation and reduces system buoyancy, leading to increased maintenance costs, which are estimated at 5–10% and potentially up to 30–50% of total production costs (Fitridge et al., 2012; Hincapié-Cárdenas, 2007; Méndez, 2007; Pacheco & Garate, 2005; Romeu & Mergulhão, 2023; Ross et al., 2004; Wahl, 1989). Moreover, indirect costs can occur, derived from the loss of gonadal weight due to stressors experienced during culture, which affects company profitability. Under the environmental conditions of this study, replacing lantern nets proved beneficial, reducing biofouling biomass by 84.28 kg lantern net⁻¹ (63.9% reduction compared to T2), equivalent to 25.28 t ha⁻¹. This significantly reduces the load on each net, thereby minimizing the need for maintenance related to refloating culture lines.

On the other hand, if lantern nets are replaced (cleaned and redeployed) during culture, harvesting operations would be more maneuverable and efficient: hoisting the nets onto the vessel would be simpler and transferring them from the culture lines to the processing platform would be faster, resulting in fuel savings. On the operating platform, the activities of deactivating the lantern nets (i.e., opening the lantern nets and removing the target organisms) would also be much easier and require less physical effort, with a lower risk of cuts for the operators. Consequently, these improvements could lead to increased operational efficiency and reduced labor costs during the harvesting process. The transfer of lantern nets from the operating platforms to port would be less frequent, as only heavily fouled nets will be sent ashore for deep cleaning, while cleaned nets are immediately redeployed (Fitridge et al., 2012). Although this method requires two on-site hoisting operations per net, the overall reduction in long-distance trips lowers vessel time and maintenance costs. Care must be taken as the extra handling at sea can increase labor time and may stress the scallops (Wahl, 1989). Although a large volume of biofouling waste is produced throughout the culture period, our method reduces the amount per net change, allowing for easier and more manageable disposal in smaller batches.

Additionally, it should be mentioned that the decrease in biofouling production contributes to the conservation of benthic biodiversity as there is less feces and biofouling released naturally or during routine activities, toward the bottom of the bay, which forms benthic mats (Romeu & Mergulhão, 2023). The reduction of biofouling also decreases the production of phosphates, ammonium, and nitrates, which encourage the eutrophication of the ecosystem (Camargo & Alonso, 2007), which indirectly threatens business profitability.

4.2 | Growth of *A. purpuratus*

Under the conditions in which *A. purpuratus* is cultured in Samanco Bay, biofouling with a biomass 2.8 times higher in T2 than in T1 (Table 1) definitely affects the development of the cultured organisms. Many parameters were measured and compared between T1 and T2, including valve height, gonad weight, adductor muscle weight, GSI, CF, and commercial yield indexes (Figure 5). All these values were higher in T1 than in T2, ranging from 1.13 to 2.76 times greater. The causes that explain the results would likely be due to limitations in T2 relating (or with regards) to the renewal of oxygen and seston inside the lantern nets and the accumulation of particulate and dissolved organic matter, and additionally, we hypothesize that contact with *C. intestinalis* may be causing stress to the organisms. However, *A. purpuratus* is a species that regulates critical points of low oxygen (Aguirre-Velarde et al., 2016; Cueto-Vega et al., 2022), living between 0.2 and 9 mL O₂ L⁻¹ (Yamashiro et al., 1990; Mendo et al., 2001; González Hunt, 2010; Aguirre-Velarde et al., 2016), with the capacity to maintain for up to 12 hours an active filtration rate under conditions of low oxygen saturation (Aguirre-Velarde et al., 2018). However, the organisms would have consumed their body energy reserves (Grieshaber et al., 1988) during conditions of hypoxia (<2 mg L⁻¹; Storey & Storey, 2004) or prolonged anoxia that may have occurred due to cessation of photosynthetic activity, algal bloom, and cellular respiration in the bay and inside the lantern nets, more severe at times with less water movement. This would have significantly affected the metabolic rate of the organisms (Montúfar-Romero et al., 2024), with repercussions on growth, more in T2 than in T1 (Table 3).

Despite the negative effects of biofouling in Samanco Bay, the results in both treatments (Table 3) exceed those obtained for the same species in Mejillones Bay (Chile) with adductor muscles of 10.2 ± 1.4 g in obstructed lantern nets, and in Tortugas Bay (Peru), with gonad weights between 9.21 and 9.86 g, where biofouling would not have been a problem (Cano Maguiña, 2004). On the other hand, in *A. purpuratus* culture in Pucusana (Peru), RIGR values of 0.133 to $0.245 \text{ mm day}^{-1}$ have been obtained (Cisneros et al., 2008), in Casma (Peru) between 0.11 and 0.38 mm day^{-1} (Alcázar & Mendo, 2008), and in Paracas Bay (Peru) between 0.25 and 0.39 mm d^{-1} . These values are similar to the values obtained at T1 in the present study; however, they are very distant from the value at T2 (Table 3), an effect attributable to excessive biofouling development.

In the natural environment, the GSI of *A. purpuratus* varies between 8% and 30% (Avendaño et al., 2008; Uribe, 2003). A culture of this species, located in Tortugas Bay (Peru), recorded a GSI between 15.87% and 18.26%, without mentioning problems due to biofouling, and in Isla Lobos de Tierra (Peru), it was registered between 16.8% and 20.1% (Carbajal et al., 2005), which are values similar to those found in the present study (Table 3 and Figure 5). However, the lantern net exchange favored the increase of GSI in T1, being 1.24 times higher than that in T2 (Table 3 and Figure 5). These values align with the Condition Factor (CF), which correlates food availability with physiological health, and suggest that organisms in T1 were more robust than those in T2. For the same species, another study reported FC values between 5.88% and 6.64% (Carbajal et al., 2005), coinciding with those obtained in the present study, taking into account that FC can reach 20.2%. The CYI of the adductor muscle (CYI_{am}), from the point of view of its increase in weight, at T1 was 1.5 times higher than that at T2, reflecting better conditions at T1 due to lantern net exchange. In culture conditions of *A. purpuratus* (La Paz, Mexico), CYI_{am} values were between 20% and 30% (Cáceres-Martínez et al., 1990), which are similar to those of the present work.

4.3 | Survival

Naturally, the survival of *A. purpuratus* is influenced by several factors, such as density, predation, food availability and quality, temperature, salinity, and dissolved oxygen in the water (Mendo et al., 2016). Considering that the culture of this species in Samanco Bay developed under adequate density, without predators, abundant food, stable temperature, and salinity (Figure 6), the negative effects on survival (Table 4) are reduced to oxygen conditions. As mentioned above, the development of biofouling on the lantern nets would have restricted oxygen renewal, much more in T2 than in T1, having generated in some moments of calm waters at night, conditions of prolonged anoxia, and therefore death by asphyxiation of organisms (Arakawa & Gillmor, 1980; Wahl, 1989). Furthermore, coastal upwelling (Chavez et al., 2008; Levin et al., 2009), which is frequent in Samanco Bay, would also have contributed to oxygen depletion, as the waters naturally contain low oxygen concentrations. However, oxygen depletion would have been attenuated because the study was conducted during the local winter period, when waves and currents are naturally higher due to the effect of increased winds (Table 5). This natural increase in water movement likely contributed to the high survival in T1 (97.4%) and also in T2 (86.6%) (Table 4). Waves would have caused vertical movements of the lantern nets, allowing a level of water renewal sufficient to provide oxygen and avoid significant mortality (Kristiansen et al., 2015).

It is important to consider the capacity that bivalves have to close their shells hermetically in adverse conditions, modifying their respiratory process for several hours (Galtsoff, 1964). This ability increases their capacity to live under low oxygen conditions. As mentioned, *A. purpuratus* can live at oxygen levels between 0.2 and 9 mL L^{-1} (Aguirre-Velarde et al., 2016; González Hunt, 2010; Mendo et al., 2001; Yamashiro Guinoza et al., 1990), which would have also contributed to face eventual hypoxia and anoxia conditions during the trial. Cultures of *A. purpuratus*, in Carbon Beach (Peru), obtained a survival of 70% at a density of $20 \text{ org floor}^{-1}$ at 7 m depth and lantern nets covered with biofouling, indicating that this did not interfere with water flow (Cisneros & Argüelles, 1996).

TABLE 8 Comparative summary of biofouling control techniques in marine mollusk cultivation.

Technique	Advantage	Disadvantage	Reference
Mechanical cleaning	Easy and very operational.	Cost of investment in cleaning discs. Damage to meshes.	IOC-UNESCO and GEF-UNDP-IMO GloFouling Partnerships (2022)
Air drying	Eliminating species that do not tolerate prolonged desiccation.	Prolonged time to eliminate organisms with calcareous structures or tubes, generating stress, reduced growth, and mortality in the species in culture. Heat kills but does not remove fouling.	Fitridge et al. (2012), IOC-UNESCO and GEF-UNDP-IMO GloFouling Partnerships (2022), Marine Pest Sectoral Committee (2018)
Fresh water and salt baths	Useful for eliminating some species.	Can be expensive. Does not remove algae, tunicates, organisms with calcareous shells, or tubes. May cause reduced growth and mortality in cultured organisms.	Fitridge et al. (2012), IOC-UNESCO and GEF-UNDP-IMO GloFouling Partnerships (2022), Marine Pest Sectoral Committee (2018), Hood (2020)
Heat treatment	It is most effective during the winter on soft-bodied organisms.	Organisms with calcareous shells need higher temperatures and prolonged exposure. May cause mortality in cultured organisms.	Fitridge et al. (2012), Bannister et al. (2019)
High-pressure water jet cleaning	Effective for many biofouling organisms, with little damage to cultured organisms	Costly. Fragments settle to the bottom of the ecosystem. Colonial organisms may suffer fragmentation and recolonize. May affect growth of cultured species.	Fitridge et al. (2012), IOC-UNESCO and GEF-UNDP-IMO GloFouling Partnerships (2022), Marine Pest Sectoral Committee (2018)
Chemical treatment	Chlorine, hydrogen peroxide, and acetic acid can be effective	Its use in the aquatic environment is regulated by law. May cause mortality in cultured organisms.	Fitridge et al. (2012), Bannister et al. (2019)
Antifouling coatings of silicone	Effective in inhibiting larval settlement of the coated surface, from 2 to 6 months. Easy to clean. Biodegradable and nonpersistent in the environment.	In development. Significantly increases the weight of the structures. Very high costs.	Fitridge et al. (2012), Bannister et al. (2019), Mann (2013), Swain and Shinjo (2014), Archana et al. (2019)
Toxic coatings (Cu)	Effective in preventing settlement and growth of fouling organisms for 3–6 months.	Does not prevent biofouling during the entire production cycle. Significantly increases the weight of structures. Bioaccumulation in tissues of cultured organisms. May bioaccumulate in native consumer organisms, and accumulate in sediment.	Fitridge et al. (2012), Mann (2013), Swain and Shinjo (2014), Archana et al. (2019), Qiu et al. (2021)
Biological control	Useful in small-scale shellfish culture.	Not all biofoulers have suitable natural predators. No significant advances have been made in the use of biological control	Fitridge et al. (2012), Bannister et al. (2019)

TABLE 8 (Continued)

Technique	Advantage	Disadvantage	Reference
Lantern net replacement	Reduces more than 50% of biofouling. Maintains water flow inside lantern nets. Simple technique. Improves crop yield.	Requires more lantern nets. Increases labor.	This study

4.4 | Abiotic factors

The conditions in the bay where the study took place can be considered normal, with a slight increase in water temperature during the first month and an increase in winds and waves, typical of the autumn and winter seasons in the locality at the end of the trial (Table 5 and Figure S2). This last condition, which was coincident with the wind conditions for the Chimbote area in July and October 2014, between 4.9 and 6.4 m s⁻¹ (WOESPANA, 2015), would have likely allowed the maintenance of dissolved oxygen concentrations inside the lantern nets above 5 mg L⁻¹ (Figure 6). On the other hand, these condition would have increased the speed of the surface current, consequently improving the circulation of water inside the lantern nets, and with it the contribution of oxygen and seston, favoring the development of *A. purpuratus*, at the moment of greatest colonization of the lantern nets. In addition, this water flow would have contributed to the dispersion of the feces and pseudofeces of the organisms in the culture and of the biofouling produced inside the lantern nets, thus decreasing the biochemical oxygen demand due to bacterial action (Cranford et al., 2003).

4.5 | Economic aspects

From the productive perspective, in terms of gonads and adductor muscle, the replacement of lantern nets (T1) is 25.6% higher than the production under conventional cultivation (T2). This means, in terms of gross income, 8063.1 US\$ ha⁻¹ more than in conventional cultivation (Table 6). On the other hand, the cost of operations to implement the lantern net exchange (Table 7), including lifting the biofouling-laden lantern nets, transporting, washing, repairing, and replacing them, was 1480.52 US\$ ha⁻¹. This is equivalent to 18.36% of the gross income. In other words, if the companies that cultivate *A. purpuratus* decided to implement the lantern net exchange technology, they could have a net profit of 6582.58 US\$ ha⁻¹, sufficiently attractive for investors in this field of aquaculture.

Notwithstanding the net economic advantages of duplication of lantern nets exchange, there are other advantages, as: (a) a greater weight of gonads and adductor muscle is obtained (Tables 2 and 3), improving the quality of the export product and therefore the reputation of the company; (b) 25.28 t ha⁻¹ less biofouling would be produced, representing a 63.91% reduction compared to conventional culture (Table 1), which means savings in costs for refloating lines, cleaning, and repairing lantern nets, as well as savings in the final disposal of biofouling residues; (c) mitigate the risk, which in conditions of low marine dynamics, is reflected in stress of the organisms and with it a decrease in the final weight of gonads and adductor muscle; (d) even though it has not been quantified, it would significantly reduce the disposal of feces and pseudofeces generated by biofouling, as well as the detachment of these organisms in the same concession, which would guarantee the maintenance of adequate ecosystem conditions, contributing to the sustainability of the industrial cultivation of *A. purpuratus*.

However, while the economic benefits of lantern net replacement are clear, it is important to acknowledge and address the potential environmental trade-offs associated with this practice. The cleaning and handling of biofouling material may involve the use of chemicals, generate waste, and potentially impact the surrounding aquatic environment if not managed properly. A more comprehensive assessment of these environmental implications, including

long-term ecological effects and sustainable waste disposal practices, is necessary to ensure that the proposed method balances economic profitability with environmental responsibility.

In general, there are few publications on the economic aspects of scallop farming (Cano Maguiña, 2004) and less on biofouling, even though this problem is closely related to economic profitability, as it interferes with yield, mortality, and sometimes product quality (Flemming, 2011). A study has pointed out that the impact of fouling on the production costs of the mussel industry in Scotland is estimated at 650,000 euros per year per farm and adds that the problem will increase (Campbell & Kelly, 2002). Given the problems that biofouling represents in general for large-scale mariculture, it is necessary to strengthen studies aimed at its mitigation as this would contribute to improving economic profitability and also reduce the impact on the ecosystem.

4.6 | Techniques to control biofouling

Employing the criteria of a previous study (Bannister et al., 2019), lantern net replacement is an in situ treatment technique, which significantly reduces biofouling production (by 64.6%), is economical (equivalent to 5.7% of gross income), is simple (only changing lanterns), and has a positive environmental impact by reducing biodepositions of biofouling organisms and the degree of detachment of these, which would accumulate on the bottom. This is a cost-effective technique for lantern net culture, as it results in an increase in the production of gonads (52.5%) and adductor muscle (62.4%). The removal of biofouling from the changed lanterns is done outside the bay, thus avoiding a negative impact on the aquatic ecosystem, with the possibility of turning into nutrients. On the other hand, another study argues that the strategies that must be met by techniques aimed at controlling the development of biofouling in mollusk aquaculture are expected to (a) be effective against a wide range of fouling taxa, (b) be environmentally benign, (c) have no negative effects on cultured species, (d) leave no residues on cultured species, (e) be able to withstand onshore handling and cleaning, and (f) be economically viable; characteristics that are evident in the lantern nets replacement technique, as can be evidenced when compared to other techniques related to the same purpose (Table 8).

5 | CONCLUSION

Under the conditions in Samanco Bay, exchanging lantern nets during the final stage of suspended culture of *A. purpuratus* significantly reduced biofouling production from 131.87 to 47.59 kg per lantern net. This reduction, equivalent to 25.28 t ha⁻¹, resulted in improved gonad yield (16.02%), adductor muscle weight (37.89%), and survival rate (10.8%) in Treatment 1 compared to Treatment 2. In economic terms, this means an additional net income of 6582.58 US\$ ha⁻¹. Furthermore, the reduction of biofouling generates economic advantages by reducing operating costs for refloating lines, transfer, washing, and repair of lantern nets, with potential environmental benefit by reducing the production of biodepositions and disposal of biofouling in the same concession, contributing to the balance of the water column and the conservation of the benthic community. Finally, to validate these results, this methodology must be applied on a broader scale by some of the *A. purpuratus* culture companies in the Pacific region.

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The authors declare no conflicts of interest.

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