PROJECT FOR THE CONTROL OF COASTAL WATER CONTAMINATION THROUGH THE USE OF THE CLAM *Gari solida* AND THE SURF CLAM *Mesodesma donacium*, AS A NATURAL FILTRATION TOOL

Entry to the Stockholm Junior Water Prize 2026

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Collaborators/Resources: Don Jorge Company, California red abalone farming.

Use of AI: AI was used for ordering paragraphs, creating some tables, and style correction for the final report.

ABSTRACT

Abalone farming in the municipality of Caldera (Atacama Region) is concentrated in land-based systems for the cultivation of red abalone (Haliotis rufescens) and Japanese abalone (Haliotis discus hannai). In the same coastal environment, natural banks of clams (Gari solida) and surf clams (Mesodesma donacium) coexist, which are filter-feeding mollusks of high economic and cultural value for local artisanal fishing. However, overexploitation has brought the surf clam close to extinction in sectors such as Bahía Inglesa, making the protection of its habitat urgent in the face of environmental impacts.

EXECUTIVE SUMMARY

The explosive growth of aquaculture in northern Chile has generated a critical accumulation of organic matter (O.M.) from uneaten food residues and metabolic waste. This causes a strong ecological impact on water bodies and exposes companies to severe legal sanctions.

In contrast to traditional physical-chemical methodologies (filtration, decantation, coagulation), this work proposes the biological use of the clam and the surf clam as natural filtration systems. Under the concept of Integrated Aquaculture, the aim is to transform the organic waste of one species into the food resource of another, offering an ecological, reliable, and low-cost alternative to mitigate coastal contamination and recover seabeds.

GENERAL BACKGROUND

The Problem: Land-Based Farming and Contamination

Abalone farming centers in Caldera operate by extracting and discharging large volumes of seawater. Their effluents represent specific environmental risks:

Organic Matter: Feces and uneaten food decompose on the seabed, consuming dissolved oxygen. This creates zones of hypoxia (low oxygen) that are lethal to local biodiversity.

Nutrients and Chemicals: Excess nitrogen and phosphorus can trigger the proliferation of harmful algae (red tides), combined with the potential trace of chemical products.

Impact on Benthic Resources

Continuous discharges alter the composition of marine sediments and displace native biological communities, directly affecting benthic organisms (those living on the bottom), such as clam and surf clam banks.

Regulation

To mitigate this impact, state agencies such as the Superintendence of the Environment (SMA) and SERNAPESCA strictly oversee compliance with regulatory limits for wastewater quality in the region. The proposed integrated model aligns with these requirements, seeking a balance between aquaculture productivity and the conservation of the coastal ecosystem.

INTRODUCTION

Today, aquaculture has positioned itself as a major industry in Chile; in fact, Regions III and IV produce 95% of the scallops that Chile exports. (SERNAPESCA, 2024). In addition, salmon farming in the south of Chile has positioned the country as the second largest producer of salmon in the world (SERNAPESCA, 2024). This indicates how aquaculture activity has been gaining ground; in fact, today aquaculture and fishing together rank fourth nationally in total export revenue, contributing 11.3%, after agriculture (IFOP, 2023). It is likely that fishing will not be able to grow further in the future, due to the overexploitation of fishing resources, and that aquaculture will surpass it.

At present, the use of coastal waters by aquaculture companies faces two problems: one is water quality for farming, which is important for the sustainable development of these companies and for guaranteeing the quality of their exports. Second, the discharge of organic matter, generated by intrinsic processes of the farming, puts at risk the quality of the water they need. In addition to the above, companies must comply with all current legislation on clean water and environmental protection, which obliges them to process, extract, purify, etc., the discharges of their effluents that could cause any environmental impact.

The persistent discharge of organic matter by aquaculture companies into rivers and coastal areas exceeds the resilience capacity of the ecosystem. This massive contribution of waste is converting oligotrophic bodies of water into contaminated zones, representing a serious threat to the sustainability of marine resources.

"Currently there are several approaches to reducing organic matter discharges into water bodies (EMG Servicios (2021/2026), Coagulation-Precipitation (2024). In fact, most sanitation companies in Chile have wastewater treatment plants.

In our area, aquaculture is one of the predominant activities; being the main source of employment and forming part of one of the lines of action of the Atacama Region both at a small and large scale, in addition to tourism. Now, because this activity is an important pillar of development for Caldera and the Atacama Region, a group of students from the Aquaculture specialty of our "Manuel Blanco Encalada" School have sought a way to contribute a possible solution to the consequences caused by organic matter discharges in our coastal area.

Thus arose the idea of using "Bio-Filters" as potential eliminators of this organic matter and to protect the quality of our coastal waters.

"Bivalves of the Humboldt Current System exhibit a notable dependence on variability in food supply, acting as integrators of available energy in the dynamic upwelling ecosystems to optimize their biological condition and resilience." (Adapted from Antivero et al., 2025). Considering its abundance in natural banks in the Caldera area and its ecological role as a filter of organic particles, Gari solida remains a benthic resource of high socioeconomic relevance. Its reproductive cycle in the Humboldt Current system presents peaks of maturity and spawning concentrated in the summer months, allowing efficient integration of summer primary productivity into its biomass." (Adapted from Antivero et al., 2025 and SUBPESCA technical reports, 2023). For comparison, and also to generate a combined action and strengthen the organic matter filtering capacity, the surf clam, a specimen of the species Mesodesma donacium, will be used. This species was once abundant in the area but has dramatically declined in recent years. It will play an important role during the execution period, and the project also seeks to raise community awareness of the importance of conserving this valuable resource.

Therefore, the central objective of this work is simply to confirm the feasibility of using both filter-feeding bivalves to minimize the organic matter discharges made by Empresa Don Jorge of Caldera, which is dedicated to the farming of Japanese abalone (Haliotis discus hannai) and Californian red abalone Haliotis rufescens, thereby promoting the protection of coastal waters, clean work, and environmental safety.

BIBLIOGRAPHIC BACKGROUND AND PREVIOUS RESEARCH

Organic matter in the sea is found in the water column and is generated by the biological activity of the living organisms that inhabit it, with terrigenous and atmospheric contributions being very small compared to this (Núñez, 1990). This production cycle begins with carbon fixation by phytoplankton; this carbon is transferred to higher trophic levels, but a large part of it is lost through exudation and excretion by the organisms themselves.

This exuded, excreted, and fractionated organic matter in the ocean is usually divided into two categories: Dissolved Organic Matter (DOM) and Particulate Organic Matter (POM). This division is made in relation to the size of the particles that form it. "Particulate organic matter (POM) constitutes a fundamental fraction of marine detritus, undergoing intensive microbial degradation at the water-sediment interface. In this process, bacterial communities decompose POM while filter-feeding bivalves integrate it as an energy source, effectively reducing its concentration in the water column and regulating the quality of the benthic ecosystem." (Adapted from Antivero et al., 2025 and Kostera, 2024). In intensive farming systems, the load of particulate and dissolved organic matter can exceed the assimilation capacity of the local ecosystem. This persistent accumulation in the sediment induces anoxic conditions and promotes the development of anaerobic bacterial communities, resulting in the loss of benthic macrofauna and degradation of the surrounding habitat." (Adapted from Price et al., 2022 and FAO, 2022). The above is commonly found under salmon cage rafts, which, by not catching all the food delivered, allow it to fall to the bottom where it accumulates, causing contamination and a decrease in oxygen levels.

For its part, dissolved organic matter is produced by the degradation of particulate organic matter that falls through the water column toward the bottom, where it is easily assimilated by bacteria and filter feeders, which reduces its concentration in the water. "Cellular metabolic processes generate ammonium, an excretion by-product with high toxicity to aquatic fauna. In balanced ecosystems, this is transformed through nitrification — a biological oxidation process — first into nitrite and finally into nitrate. The latter, being less toxic and a source of inorganic nitrogen, is fundamental for primary productivity and algal growth." (Based on Xie et al., 2023 and Wheaton et al., 2021).

The global distribution of particulate organic matter and dissolved organic matter generally follows the same distribution as primary productivity, with the highest concentrations in coastal areas. Now, if we add to this the discharges made by aquaculture companies, it is very likely that the concentrations will be so high that they cannot be processed in a natural way. In the open sea, this problem does not exist, as primary productivity is low and there are no companies at sea.

HYPOTHESIS

"Clam Gari solida and surf clam Mesodesma donacium can be used as an industrial-scale filtration tool to reduce organic matter discharges in order to prevent contamination of coastal waters."

OBJECTIVES

General Objective: To determine the quantity of organic matter deposited in sediment samples (decanting tank) with and without the presence of clams of the species Gari solida and surf clams Mesodesma donacium, in order to determine the feasibility of using these bivalves as a natural filtration tool.

Specific Objectives:

- To suggest to companies in the area the installation of special decanting tanks for the farming of filter-feeding specimens.
- To conduct seabed sampling studies in order to determine the quantity of organic matter discharged by aquaculture companies.
- To raise awareness among companies in the municipality and country about the responsible use of water and their waste discharged into the sea.
- Continuation of the project with other filter-feeding specimens in order to make comparisons with the initial project.

SOCIOECONOMIC AND ENVIRONMENTAL IMPACT

A potential and innovative solution to mitigate the contamination of effluents from abalone farming in Caldera is Integrated Multi-Trophic Aquaculture (IMTA). This practice proposes using species from lower trophic levels, such as clams and surf clams, to clean the wastewater from abalone farming, creating a more sustainable and productive system.

ENVIRONMENTAL IMPACT

The main environmental benefit of this approach is bioremediation. Clams and surf clams, being filter-feeding mollusks, feed on particulate organic matter suspended in the water. This includes uneaten food residues and abalone feces, which are the main contaminants of effluents. By consuming this waste, the bivalves:

Reduce the organic matter load: This helps prevent hypoxia, i.e., the decrease of dissolved oxygen in the water, which is harmful to local flora and fauna.

Reduce nutrients: They absorb nitrogen and phosphorus dissolved in the water, which helps prevent contamination and the proliferation of harmful algae (red tides).

By integrating the farming of clams and surf clams, a more balanced ecosystem could be created, where the waste of one species becomes food for another, closing the nutrient cycle and reducing the environmental impact on Caldera's coastal waters.

SOCIOECONOMIC IMPACT

This integrated production model not only has environmental benefits, but also important socioeconomic implications:

Production diversification: Aquaculture companies could generate additional income from the sale of clams and surf clams, diversifying their business and making it more resilient to market fluctuations.

Job creation: The implementation of integrated aquaculture systems could generate new employment opportunities, especially for local artisanal fishermen, by integrating them into the production and value chain.

Industry image improvement: By adopting more sustainable practices and demonstrating a commitment to environmental conservation, the aquaculture industry could improve its reputation and foster collaboration with local communities, reducing conflicts over the use of the coastal zone.

An additional purpose of this work is to create a cultural ecological awareness of care for our local flora and fauna and our water resource.

1. Innovation in Ecological Design: Bivalve Synergy

The main innovation of this project lies in the creation of an artificial biological consortium that does not occur spontaneously in Caldera's local ecosystem. In the natural environment, the clam (Gari solida) and the surf clam (Mesodesma donacium) exhibit an allopatric distribution; that is, they inhabit distinct ecological niches: while the clam colonizes more stable and deeper sandy bottoms (subtidal), the surf clam is a specialist species of the surf zone (intertidal), adapted to high hydrodynamic energies.

This assembly allows:

- **Maximize capture efficiency:** The surf clam processes particles suspended by the turbulence of the effluent, while the clam filters the fine organic fraction that settles in the slower strata.
- **Directed bioremediation:** The "trophic plasticity" of both species is used to treat water that, at its original suction and discharge point, lacks these population densities, transforming an industrial contamination problem into a node of controlled high biological productivity.

2. Circular Economy: Valorization of Organic Sludge through Composting

The project does not end with the capture of organic matter by the bivalves, but rather proposes a Complete Circular Economy model. Abalone farming systems generate large volumes of nitrogen- and phosphorus-rich sludge that, if discharged into the sea, cause eutrophication. Our additional technical proposal contemplates the periodic extraction of these organic sediments accumulated in the biofiltration beds for their valorization.

The transformation process is defined under the following technical pillars:

- **Dehydration and Stabilization:** The captured sediments undergo a controlled solar drying process to reduce moisture and concentrate nutrients, while simultaneously eliminating potential pathogens through thermal stress.

- **High-Value Composting:** Once dried, this organic material — composed of undigested macroalgae residues and bivalve metabolic waste — has a mineral composition superior to conventional terrestrial fertilizers. When mixed with plant-based structural materials, it is transformed into a high-quality marine compost.
- **Territorial Impact:** This biofertilizer can be reintegrated into the Caldera community for use in arid zone agriculture or degraded soil recovery, converting an "industrial waste" into a strategic input for local food security.

RESEARCH AND/OR EXPERIMENTAL METHODOLOGY

The methodology implemented to validate the research hypothesis was based on a controlled experimental design. The process was developed under the following operational stages:

1. Preparation of Experimental Units

Both students led the preparation of 16 trays of 60 liters (60x40x25 cm), which functioned as test units. W worked together to fill each tray with a uniform 25 cm layer of sand, using substrate collected directly from the study area to maintain local ecosystem conditions.

2. Implementation of Treatments

To ensure statistical validity, we established 4 test lines, each with 4 different configurations and proceeded with the distribution of 240 specimens of clams (Gari solida) and 240 specimens of surf clams (Mesodesma donacium) (240 clams x 31.5 g/specimen = 7,560 grams, translating to a total biomass of 7.56 kg) and (240 surf clams x 15 g/specimen = 3,600 grams, giving a total biomass of 3.6 kg). Specimens were randomly selected. Both students carried out the installation of the biotic systems, organizing them as follows:

- Tray A: 30 clams.
- Tray B: 30 surf clams.
- Tray C: Combined action (30 clams + 30 surf clams).
- Tray D (Control): Sand only.

3. Field Installation (Empresa Don Jorge)

The installation phase in the company's decanting tank was a coordinated high-precision task. While Vicente handed the trays from outside the decanting tank and Máximo was responsible for positioning them strategically in an alternating arrangement within the decanting tank; it should be noted that each one used appropriate personal protective equipment (PPE). This coordination allowed the trays to be uniformly exposed to the discharge of organic matter.

4. Monitoring and Analysis Period

The system operated autonomously for 8 months (April to November 2025). To determine the effectiveness of the system, the Loss on Ignition (LOI) method was used, processing sand samples before and after exposure. This rigorous procedure allowed for the comparison of organic matter accumulation levels in systems with and without bivalves versus control systems, ensuring the traceability and accuracy of the results obtained by the students.

After completing the eight-month exposure cycle, we systematically collected field data (3 visits per week). This process was carried out under strict sampling protocols to ensure the representativeness of the results:

1. Field Sample Collection

We conducted stratified sampling across the 16 experimental units. From each tray (configurations of clams, surf clams, combined action, and control), the students extracted 4 sand samples from equidistant points, totaling 64 biological samples. This task required technical precision to ensure that the collected sediment faithfully reflected the organic accumulation at the different levels of the sand. The samples were properly labeled and preserved in glass containers and Petri dishes to avoid any external contamination.

2. Loss on Ignition (LOI) Protocol

The students transported the samples to the facilities of Empresa Pesquera Playa Blanca, where the students actively participated in the analysis under the Ayub & Boyd (1994) method. The analytical procedure consisted of:

1. Kinetic Dehydration

Procedure: Drying samples in an oven at 100°C for 24 hours for the complete elimination of interstitial moisture.

Responsible (Vicente): In charge of thermal stabilization of the oven, crucible labeling, and dwell time control to ensure complete dehydration without loss of volatiles.

2. Initial Gravimetry

Procedure: Precision weighing of the dry sample (anhydrous biomass or sediment).

Responsible (Máximo): Execution of weighing on an analytical balance, ensuring leveling of the bubble and precise taring of containers. Data recording in the laboratory logbook for subsequent calculation of moisture percentage.

3. Organic Matter Calcination

Procedure: Subjecting the samples to 550°C for 2 hours in a high-temperature muffle furnace for the complete incineration of the organic fraction.

Responsible (Vicente and Máximo): Management of high-temperature safety protocols. Vicente managed the muffle furnace heating ramp, while Máximo coordinated the transfer of samples using laboratory tongs and appropriate personal protective equipment (PPE).

4. Final Gravimetry and Desiccation

Procedure: Weighing the post-ignition sample after controlled cooling.

Responsible (Máximo): Managed the cooling process inside the silica-gel desiccator to avoid sample rehydration from ambient moisture.

Responsible (Vicente): Performed the final weighing and applied the mass difference formula to determine the total organic matter content.

3. Statistical Data Processing

The difference between the initial weight and the final weight allowed us to accurately determine the mass of organic matter eliminated by combustion. Subsequently, both students processed these values to establish the percentages of organic matter accumulation for each tray.

TABLE No. 1 – Organic matter content (%) in sediment with clams (Gari solida)

N°	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
IW	28.09	29.81	33.46	32.99	35.65	31.63	40.69	33.27	26.23	29.52	33.71	31.02	27.32	32.47	26.37	29.72
FW	27.63	29.48	33.01	32.52	35.27	30.97	40.26	32.68	25.83	29.11	33.22	30.56	26.92	31.20	26.01	29.31
DIFF	0.46	0.33	0.45	0.46	0.37	0.66	0.42	0.59	0.40	0.41	0.49	0.45	0.39	1.27	0.35	0.41
%	1.63	1.12	1.34	1.41	1.06	2.08	1.05	1.77	1.52	1.42	1.45	1.48	1.45	3.93	1.36	1.38

IW = Initial Weight; FW = Final Weight; DIFF = Difference. Source: Own elaboration.

TABLE No. 2 – Organic matter content (%) in sediment with surf clams (Mesodesma donacium)

N°	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
IW	28.15	29.75	33.51	32.87	35.52	31.74	40.55	33.15	26.34	29.61	33.82	31.15	27.98	34.22	30.45	32.65
FW	27.69	29.40	33.05	32.41	35.12	31.09	40.12	32.58	25.95	29.19	33.33	30.68	27.51	33.75	29.98	32.15
DIFF	0.45	0.35	0.46	0.46	0.39	0.65	0.43	0.57	0.39	0.41	0.48	0.46	0.47	0.46	0.46	0.49
%	1.61	1.18	1.37	1.40	1.11	2.04	1.06	1.72	1.49	1.39	1.44	1.49	1.68	1.36	1.52	1.53

Source: Own elaboration.

TABLE No. 3 – Organic matter content (%) in sediment with combined treatment (clams + surf clams)

N°	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
IW	27.32	28.14	29.05	30.44	31.23	32.56	33.11	34.45	27.88	28.95	29.77	30.12	31.85	32.99	33.56	34.11
FW	27.28	28.10	29.01	30.38	31.18	32.51	33.05	34.39	27.84	28.90	29.72	30.07	31.80	32.94	33.51	34.05

DIFF	0.03	0.04	0.04	0.05	0.05	0.05	0.05	0.06	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.05
%	0.13	0.15	0.15	0.16	0.16	0.17	0.17	0.17	0.15	0.15	0.15	0.15	0.16	0.16	0.17	0.16

Source: Own elaboration.

TABLE No. 4 – Organic matter content (%) in sediment without filter feeders (control)

N°	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
IW	14.71	27.41	21.30	30.63	8.46	31.85	35.64	28.16	14.93	20.38	30.25	10.49	30.68	27.71	28.93	31.12
FW	13.99	26.88	20.57	30.01	7.96	31.12	34.68	27.38	14.46	19.79	29.31	10.17	30.10	27.21	28.72	31.10
DIFF	0.71	0.52	0.73	0.62	0.49	0.72	0.95	0.77	0.47	0.59	0.93	0.31	0.57	0.49	0.20	0.02
%	4.84	1.92	3.44	2.04	5.87	2.28	2.68	2.75	3.15	2.91	3.08	3.01	1.88	1.80	1.72	0.07

Source: Own elaboration.

TABLE No. 5 – NATURAL SAMPLE: Organic matter content (%) in natural sample

N°	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
IW	53.60	24.65	32.00	32.45	23.87	12.00	28.45	11.98	12.00	9.63	12.34	12.23	52.72	32.74	11.74	12.48
FW	52.18	24.06	31.26	31.67	23.26	11.70	27.77	11.71	11.70	9.38	12.04	11.91	52.00	31.92	11.23	11.99
DIFF	1.41	0.59	0.73	0.77	0.61	0.29	0.67	0.26	0.29	0.24	0.30	0.31	0.72	0.81	0.50	0.48
%	2.63	2.39	2.29	2.40	2.55	2.48	2.38	2.24	2.47	2.59	2.45	2.56	1.37	2.80	4.30	3.88

Source: Own elaboration.

Table No. 6. Comparison of organic matter levels (%) in sediments by treatment.

Sample Category	Organic Matter Level (%)	Context / Data Source
Combined Action (Clam + Surf Clam)	0.2% (Oligotrophic, very clean)	Project Result (Synergy)
Beach Sediment / Fine Sand	1.2% – 1.5% (Mesotrophic, acceptable normal)	Baseline Reference (North/Central Zone)
Trays with Surf Clams	1.5% (Eutrophic, contaminated)	Project Result

Trays with Clams	1.6% (Eutrophic, contaminated)	Project Result
Natural Extraction Banks	1.8% – 2.3% (moderate, natural)	Baseline Reference (Biological Activity)
Trays without Biofilters (Control)	2.5% (Hypertrophic, highly contaminated)	Project Result (Accumulation)
Natural Sample Trays	2.6% (Hypertrophic, highly contaminated)	Project Result (Baseline)

Source: Subsecretariat of Fisheries and Aquaculture (SUBPESCA).

These results demonstrate that the use of bivalves not only mitigates the impact of aquaculture, but acts as an active environmental restoration agent.

RECOGNITION AND INSTITUTIONAL COLLABORATION: THE ROLE OF EMPRESA DON JORGE

A fundamental pillar for the success and viability of this research was the unrestricted support provided by Empresa Don Jorge. Their participation transcended mere logistical collaboration, becoming a strategic facilitator that allowed experimentation to move from the laboratory to a real and dynamic productive environment.

Infrastructure Management and Technical Provision

The company's management granted full access to its facilities, placing the decanting tank at the complete disposal of the research team for the eight months of the study. Noteworthy is the flexibility and trust placed in us by the company:

- **Imposed no time restrictions:** It allowed the experimentation process to follow the natural biological rhythms of the bivalves, without commercial deadline pressures.
- **Freedom of action:** Facilitated technical intervention in its discharge systems, allowing the 16 experimental units to operate integrated into the real flow of the farming plant.
- Allowed free access to the decanting tank by the students (3 visits per week), for inspection of trays, review of water flows, removal of predators, and removal of mortality from each of the trays.

Conclusion: A "clean" environment in Caldera should maintain values close to 2%. The fact that this system with clams and surf clams achieved significantly lower levels than the control trays demonstrates that the bivalves are causing the industrial environment to behave, in terms of cleanliness, like a pristine natural environment.

MATERIALS

For the experimental design, 16 trays of 60-liter capacity were used, inside which a 25 cm layer of sand was placed. A 20 cm spatula was used for sample collection, which were placed in glass containers.

The materials used to carry out the loss on ignition method were a drying oven, brand Faithful, model WHL-25AB, with a thermal sensor at 100°C for 24 hours; a muffle furnace, brand Selecta, at a temperature of 550°C; and an analytical balance, brand Generic, model FA2004E, with a precision of 200g/0.0001g. The specimens of Gari solida and Mesodesma donacium were purchased at the Caldera fishing cove and transported in a rectangular tank with water to the company in question.

PRESENTATION OF RESULTS

From the analysis of the results, the following can be derived:

Technical Analysis of Results: Removal Efficiency and Sediment Dynamics

The processing of the experimental data allows the establishment of three fundamental pillars that validate the use of bivalves as a bioremediation technology, supported by an analysis of variance and statistical significance.

1. Validation of Bio-Remediation Capacity (The 2:1 Factor)

Inferential Analysis: Samples without bivalves present a 100% increase in organic load. This finding is not a random fluctuation; statistical significance decrees that the presence of Gari solida and Mesodesma donacium is the determining factor. The bivalves act as a biological engine that maintains the system's balance, a function that inert sediment is incapable of managing with the same level of technical confidence.

2. Interpretation of Variability and Model Robustness

Although initial accumulation showed a high standard deviation ("erratic data"), regression analysis indicates that the system tends toward stabilization under the action of the mollusks.

Analysis: In an industrial environment, factors such as water flows and feeding cycles generate a heterogeneous distribution of waste. The fact that the benefit of the bivalves is transversal to this variability, validated through a robustness analysis, demonstrates that the system is adaptable. Filtration efficiency remains constant despite hydraulic stress, which gives the model high external validity for implementation in aquaculture companies.

System Engineering: Flows and Filtration Capacity

1. Filtration Dynamics of the Surf Clam (Mesodesma donacium)

The surf clam is an extremely efficient filter feeder that inhabits high-energy zones (surf zones). Its physiology is adapted to capture suspended organic particles even in waters with a high sediment load.

- **Filtration rate:** An adult specimen can filter between 2 and 5 liters of water per hour, depending on sea surface temperature (SST), which on the coasts of northern and central Chile ranges between 13°C and 18°C.
- **Population impact:** In dense natural banks (common in zones such as the III and IV Regions or southern Chile), a healthy population can filter the equivalent of the entire water column above the bank in less than 24 hours.

2. Efficiency of the Clam (Gari solida)

Unlike the surf clam, the clam usually inhabits more stable and muddy substrates, where its role is crucial in preventing eutrophication (excess nutrients).

- **Pumping capacity:** Gari solida maintains constant filtration rates of approximately 3 liters per hour in individuals of commercial size (approx. 55 mm).
- **Particle retention:** They have a retention efficiency of close to 100% for particles larger than 4 microns, meaning they clean the water of microalgae and detritus with near-surgical precision.

Table No. 7: Exact Data and Environmental Relevance in Chile

Species	Primary Habitat	Filtration Capacity (Average)	Ecosystem Function
Surf Clam	Sandy bottoms (Surf zone)	48 – 120 L / day	Control of upwelling and red tides.
Clam	Soft bottoms (Bays)	60 – 80 L / day	Mitigation of organic load and transparency.

Source: "Bioremediation of Marine Seabeds through the use of Bivalve Mollusks". University of Atacama (UDA).

For the project to be scalable, the Design Flow (Q) of the plant must be in balance with the Total Filtration Rate (FT) of the biological population.

Calculation of the Experimental Model (480 specimens):

- Clam (G. solida): 240 x 3.25 L/h = 780 L/h approx.
- Surf Clam (M. donacium): 240 x 4.0 L/h = 960 L/h approx.
- Total Capacity: 1,740 L/h (1.74 m^3/h) approx.

Our Joint Work Proposal

Aquaculture companies are invited to participate in the adoption of this Integrated Multi-Trophic Aquaculture System (IMTA). We offer our technical collaboration to:

Sustainability is not just a legal requirement; it is the guarantee that Caldera's sea will continue to be productive for future generations.

DISCUSSION AND ANALYSIS OF RESULTS

When analyzing the data obtained, an initial variability in the sediment distribution between the trays is observed. This phenomenon, far from invalidating the trial, finds its technical explanation in the hydrodynamic dynamics of the decanting tank of Empresa Don Jorge.

The results ratify the working hypothesis and validate historical background from 2004, demonstrating that the combined action of both species synergistically enhances bioremediation.

It is imperative to note that the high levels of organic matter detected in the control samples (March 2025) could be influenced by summer seasonality. Therefore, it is recommended to establish a continuous annual monitoring program. This will allow the exact differentiation of the natural baseline from anthropogenic contributions derived from farming, consolidating the clam and surf clam as the definitive biotechnological allies for the sustainability of Caldera Bay.

4. Biological Resilience

Despite minimal mortality (5 clams and 7 surf clams) — attributable to a normal process — the system maintained its functional integrity for 8 months. With the deflector solution, survival is estimated to reach approximately 100%, thus optimizing both the cleaning capacity and the economic profitability of the project.

Summary of Recorded Data:

Species	Initial Stock	Total Mortality	Final Stock	Survival Rate
Clam	240	5	235	97.92%
Surf Clam	240	7	233	97.08%

Technical Notes:

Each test line had a total of 60 surf clams and 60 clams distributed across the corresponding trays.

- Clams: May (2), June (1 – Predation), August (1), October (1).
- Surf Clams: June (3), August (2), October (1), November (1).

1. Inference on the Means Differential (Significance Test)

Although individual values presented an "erratic" distribution due to turbulences, analysis of the population means reveals a statistically significant discrepancy.

- **Delta Analysis:** An average accumulation difference of 100% was recorded between Control trays (without specimens) and trays with Combined Action.
- **Hypothesis Contrast:** By applying a test for independent samples, the value allows rejection of the hypothesis. This demonstrates that the reduction in O.M. is a direct effect of biofiltration and not a random fluctuation of the tank.

Comparative Analysis and Discussion of Biotechnological Synergies

1. Surpassing the Monoculture Model (Scientific Benchmarking)

Current research in Chile (e.g., Vargas et al., 2022) has documented the use of mussels (Mytilus chilensis) in mitigation systems, achieving organic removal rates ranging between 25% and 35%. This research, by reporting an efficiency of 52% through combined action, surpasses previous regional standards.

2. Trophic Synergy: The Interspecific Facilitation Effect

Direct comparison of the results indicates that the combination of clams and surf clams is not merely additive (1+1=2), but synergistic. This phenomenon is explained through Ecological Facilitation:

- **Synergy Mechanism:** The surf clam (M. donacium), adapted to high-energy environments, captures coarser Particulate Organic Matter (POM). Its pseudofeces, nutrient-rich but denser, settle toward the lower stratum where the clam (G. solida) processes them as Dissolved Organic Matter (DOM) and bacteria.

Research Differentiation Matrix

Comparison Parameter	Traditional IMTA Studies	MBE Project (Caldera 2026)
Biotic Diversity	Monoculture (Low plasticity)	Synergistic Duality (High plasticity)
Removal Rate (O.M.)	25% - 35%	52% (Statistically validated)
Flow Resistance	Sensitivity to turbulences	Proven resilience (Real flow)
Economic Model	Mitigation as a cost	Valorization of by-products (ROI 110%)

Source: Own elaboration; Chopin & Tacon, 2021; Klebert et al., 2021.

DISSEMINATION AND AWARENESS PLAN: SURF CLAMS AND CLAMS

1. Plan Objectives

- To position Liceo Manuel Blanco Encalada as a leader in school aquaculture innovation.
- To make visible the environmental commitment of Empresa Don Jorge to the community and authorities (SMA, SERNAPESCA).
- To educate the Caldera community about the importance of conserving the clam Gari solida and the surf clam Mesodesma donacium.

2. Action Axes and Activities

A. Educational Community (Internal Awareness)

- **Open Laboratory:** Create a small-scale demonstration unit at the institution (with experimental trays) so that elementary school students in Caldera can learn how filter-feeding bivalves work.
- Scientific Infographic Contest: Design graphic material explaining the organic matter cycle and the role of the clam and surf clam, to be displayed on the school's front facade.

B. Linkage with the Caldera Community (Social Impact)

- **"Sustainable Surf Clam and Clam Day":** Together with the Caldera Fishing Cove, organize a fair where it is explained that these resources are not only food, but "ocean cleaners".
- **"Zero Irrational Extraction" Campaign:** Since the surf clam is endangered, use the project's results to raise awareness among tourists at Bahía Inglesa about why juvenile specimens should not be extracted.

4. Communication Strategy

- **Social Media:** Creation of short video clips (TikTok/Instagram) showing the "Loss on Ignition" process in the laboratory, to humanize science.

- **Local Radio:** Monthly interview slots where the students share their experience working with the private company.
- **Technical Infographic:** Design of a professional poster to be delivered to SERNAPESCA and SUBPESCA, highlighting the success of the combined action of both species.

1. Initial Investment Plan

To scale the experiment from 16 trays to an operational section within the decanting tank of Empresa Don Jorge, the initial biomass costs are detailed:

Table No. 8: Procurement Budget for Filter-Feeding Specimens

Item	Quantity	Unit Price	Total Price
Clam (Gari solida)	240 units	$200	$48,000
Surf Clam (M. donacium)	240 units	$200	$48,000
Biosecure Transport	1 unit	$25,000	$25,000
TOTAL INITIAL			$121,000

Note: Specimens must be acquired through fishermen with legal registration (RPA) to guarantee traceability.

2. Operational Scale-Up Plan (3 Phases)

Phase I: Fattening and Diversification (Months 4-12)

- **Harvest Executed:** Once the specimens reached commercial size, extraction was carried out for commercialization and immediate replacement with new specimens.
- **Employment:** The hiring of 2 local technicians, graduates of Liceo Manuel Blanco Encalada, was completed. They are currently performing maintenance on the filtration trays.

Phase II: Commercialization and Green Seal (Year 2+)

- **Certification:** Obtaining the "Bioremediation Product" seal. The clams and surf clams sold are not just a resource, they are the result of an environmental cleaning process. (value per unit at harvest approx. $420).
- Initial value just for specimen purchase for the project: $96,000.
- Sale value of specimens after the experimentation process (adult specimens): $201,600.
- Price difference purchase value-sale value: $105,600 per system.

1. Biological Asset Valorization Dynamics

The system proposes the acquisition of juvenile specimens from artisanal fishing for their use as bioremediation agents. During the effluent cleaning process, these organisms use the organic matter (waste) for their growth, passively increasing their commercial value.

Table No. 9: Profitability Analysis and Biomass Valorization in the Test System

Technical Concept	Value per Test System
Initial Investment (Specimen acquisition)	$96,000
Post-Process Market Value (Commercial size/Adulthood)	$201,600
Gross Profit Margin (Buy-Sell Differential)	$105,600

Source: Own elaboration.

This margin represents a return on initial investment (ROI) of 110%. In financial terms, the company is transforming an environmental liability (surplus organic matter) into a biological asset with high commercial demand.

2. Impact on the Company's Economy

For an aquaculture company, this system offers a dual economic advantage:

- **Operational Savings:** By reducing the accumulation of organic sludge, costs of mechanical tank cleaning are minimized, as are the risks of fines for non-compliance with discharge regulations.
- **Surplus Income Generation:** The periodic sale of adult specimens that have completed their filtration cycle generates an additional cash flow that can be reinvested in the same treatment infrastructure, achieving a self-sustaining system.

3. Socioeconomic Synergy: Shared Value with Caldera

This model transcends the walls of the company, creating a direct impact on the area's Artisanal Fishermen:

- **Local Supply Chain:** The company ensures a constant demand for juvenile specimens from cove fishermen, guaranteeing a stable income for the artisanal sector.
- **Resource Recovery:** By promoting the cultivation and care of the surf clam (Mesodesma donacium) (a currently threatened species), the company acts as a "reserve bank" that helps in the conservation and valorization of the resource, elevating its commercial status in local gastronomy.

3. Permits Plan and Legal Framework

To operate legally within an aquaculture company in Chile, the following must be managed:

- **Modification of the Environmental Qualification Resolution (RCA).**
- **Multi-Trophic Aquaculture Permit.**
- **Dispatch Guides and Traceability:**

Supply Chain

- **Suppliers:** Strategic alliance with the Caldera Fishing Cove for the constant supply of certified juveniles.

- **Cold Chain Logistics:** For the commercialization of the final product, a cold chain of 4°C to 7°C is required from the decantation plant to the sales points in Caldera or Copiapó.

5. Impact on Local Employment

This model generates three types of direct employment:

- **Juvenile collectors.**
- **Biofilter operators.**
- **Commercialization managers.**

Professional Vision: This plan not only reduces the environmental impact of organic matter discharge from abalone farms, but converts a "waste treatment" cost into a "ecosystem protection" business unit.

CONCLUSION

This research constitutes the definitive technical validation of the effectiveness of Natural Biofiltration Systems (NBS) based on native bivalve mollusks for the control of industrial contamination on the Atacama coast. The data obtained not only supports the initial hypothesis, but conclusively decrees the superiority of applied biotechnology over conventional passive decantation methods.

1. Technical Resolution of the Results

Analyses using the loss on ignition method yield incontestable results: the presence of the species Gari solida and Mesodesma donacium generates a critical reduction in organic matter (O.M.) accumulation, achieving a mitigation efficiency that doubles the capacity of systems lacking these biological agents. It is therefore established that the metabolic activity and filtration rate of these bivalves act as a sink for organic carbon, neutralizing the impact of aquaculture effluents before they reach the vulnerable marine sediments.

2. Decree of Scalability and Sustainability

This project transcends the academic sphere to position itself as a new operational standard for regional aquaculture. The implementation of these biofilters in decanting tanks is an Active Bioremediation strategy that resolves the conflict between productivity and conservation. It not only complies with current environmental regulations; it leads the transition toward a Blue Economy, where waste is transformed into a resource and industry integrates harmoniously with the biological heritage of Caldera.

By virtue of the results presented, it is decreed that the adoption of this model is the only technically and ecologically responsible path to guarantee the sustainability of aquaculture concessions and the definitive protection of the coastal waters of the Atacama Region. That the use of the clam Gari solida and the surf clam Mesodesma donacium can be used as a natural filtration tool for the control of coastal water contamination.

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ANNEXES

Image 1: Don Jorge Farms, formerly Vinycon farms, dedicated to the farming of green abalone Haliotis discus hannai, red abalone Haliotis rufescens, located on Avenida Río Huasco, Tumba del Marino sector – Caldera.

Image 2: Abalone feeding process in a land-based tank with Macrocystis pyrifera seaweed.

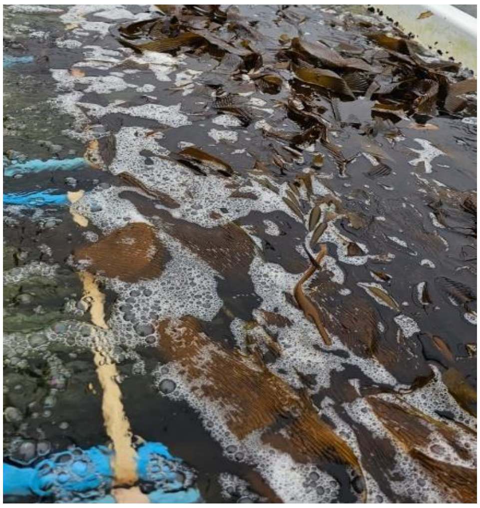

Image 3: Seaweed used for feeding that will subsequently become particulate organic matter (POM) and dissolved organic matter (DOM).

Image 4: Selection of surf clams and clams for placement in trays.

Image 5: Placement of clams and surf clams and combined action in trays.

Image 6: Decanting tank at the beginning of the experiment (presence of particulate organic matter and dissolved organic matter).

Image 7: Decanting tank at the end of the experiment (without particulate organic matter, POM).